A GAME THEORETIC ANALYSIS OF THE ECONOMICS OF DEEP OCEAN MINING

by

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"And on the credit side: Forty-six billion herrings, eight million tuna, and six hundred and fifty-two thousand manganese noodles."
INTRODUCTION

In May 1978, Soviet-supported Katangan rebels invaded the mining province of Shaba in Zaire. In December 1978 a U.S. company owned deep-sea mining vessel, the Glomar Explorer completed its first testing of ferromanganese nodules off the coast of California. These two seemingly isolated events are in fact clearly related through their implications for the future of the world markets for some key nonfuel minerals. The first event typifies the sort of disruption that has raised serious concern in Western economies about the secure supply of minerals. The Kolwezi mines in Shaba are the world's leading source of cobalt and an important source of copper. The second event carries with it the promise of an entirely new and potentially stable source of abundant supplies of cobalt, copper and nickel.

Events such as the two described earlier will determine the evolution of the world markets for cobalt, copper and nickel. Deep ocean mining for ferromanganese nodules will probably be the most significant development in the latter part of the century for at least three mineral markets. It is the purpose of this paper to investigate the evolution of the non-communist world markets for cobalt, copper and nickel following the impact of deep ocean mining for marine ferromanganese deposits. There are three special aspects to this resource:

(i) It is a multimineral or joint product resource consisting of iron, manganese, copper, cobalt, nickel and traces of elements such as molybdenum.

(ii) The technology to extract it in commercial quantities is reaching fruition at precisely the time the resource is assuming significance as a major future source of some key nonfuel minerals.
(iii) It is a resource whose legal status is in a state of transition from a transnational to supranational resource (S-Resource).*

The impact of ocean mining is likely to result in the following consequences:

-- The non-communist world markets for cobalt, copper and nickel may become very closely linked so that decisions will have to be made in all three markets simultaneously. This means that the variables for investment, production, pricing and marketing will require a simultaneous solution in three markets.

-- The prices of cobalt, copper and nickel may converge. Specifically, the price of cobalt may be driven to the marginal cost of production from offshore mining and the price of copper may rise above historical levels while the price of nickel stays fairly close to an historical average.

-- Offshore mining may, under certain assumptions, capture significant shares of the world markets for the minerals. Indeed, the entire non-communist market for cobalt, from about 25% to 60% of the market for nickel and about 20% of the market for copper may be satisfied by offshore mining.

In evaluating the impact of ocean mining the following methodological approach was adopted: the general situation is that a certain resource occurs with a certain global distribution, a fraction of which is supranational or the common property of all nations. The rest of the resource is appropriated by various nations. The supranational fraction of the resource is currently not being exploited.

It is assumed that there are two types of nations in the world, those that are net consumers (NC) of the given resource, i.e. that group of nations which consume more than they produce and those that are net producers (NP), i.e., that group of nations which produce more of the

* A transnational resource is the property of no nation. A supranational resource is the common property of all nations. By international agreement or implicit consensus among countries, no national interest or limited coalition of national interests can appropriate an S-Resource.
resource than they consume. The NC wish to initiate exploitation of the supranational resource (S-Resource) for reasons which include a desire to capture some of the rents* of production and secure access to a potentially stable, politically neutral source of supply. The NP wish to prevent exploitation of the S-Resource for fear of losing revenue, market share or political power. The NC possess the technology to develop the S-Resource, while the NP do not.

The two major questions facing these two groups of nations are:

(1) How can the rent derived from the production of the S-Resource be divided between the NC and the NP in a manner that minimizes conflict so that resource development can proceed, and

(2) What are the levels of production, price and technological royalties that accompany the distribution of rent?

Since the desire to minimize conflict is a given in the situation the structural changes necessary in world markets to accommodate the development of the S-Resource can only be brought about through a process of bargaining between the NP and the NC. This bargaining is modeled through the use of a Nash two part cooperative game to determine the unique pareto-optimal distribution of rent and the values of the price, quantity, royalty and market share variables that determine the magnitudes of rent accruing to the NP and NC.

This report is divided into four chapters. These are:

Chapter 1: Deep Seabed Mining Issues
Chapter 2: Game Model Formulation
Chapter 3: Demand Curves and Production Costs
Chapter 4: Model Results and Conclusions.

* Rents are defined to mean the difference between price and long run marginal cost of production. They include rents to ability, pure and quasi-rents.
CHAPTER 1: DEEP SEABED MINING ISSUES

Ferromanganese nodules are but one of several (implicit) S-Resources that have begun to attract the attention of planners in both corporations and governments. The interest in ocean minerals is the most visible manifestation of a general interest in all S-Resources. While there are similar issues involved in exploiting all S-Resources, they have been articulated in great detail only for ferromanganese nodules largely because of the publicity associated with the Third United Nations Law of the Sea Conference (UNCLOS III). In the sections that follow the reason for the interest in S-Resources will first be outlined and then the issues with deep ocean mining will be summarized.

The Interest in Supranational Resources

The S-Resources currently of interest are the minerals of the deep ocean bed, Antarctica, space, moon and other celestial bodies. Recent debate over the availability of resources for consumption in the future seems curiously inhibited by the notion of static resource reserve levels and has largely ignored the potential of S-Resources. These can significantly raise the levels of available minerals, energy and food.

The fresh water protein and fuel potential of the Antarctic, for instance, remain completely unexploited; the use of solar power satellites for energy generation has just begun to attract attention; systematic development of the mineral resources of the deep oceans has barely started; extra-terrestrial mining, near-earth space industrialization and colonization are proposals that have only in recent years become the serious concerns of scientists, economists and planners.

* The preponderance of the planet's fresh water resources are locked in the Antarctic.
The real concern about exhaustible resources is not that they will one day physically disappear, but that extraction costs of present reserves will rise until they become prohibitive. Accompanying this increase in extraction costs will be an increase in scarcity rent. The scarcity rent or royalty component of price will rise exponentially either as the rate of interest (Hotelling, 1931) or, if the economy is overconsuming, as some weighted average of the market and consumption rates of interest (Hanson, 1977). The total increase in price will be the sum of the increases in marginal extraction cost and scarcity rent. The increase in real price will cause a decrease in demand through a search for substitutes while an increase in scarcity rent will result in an increase in reserves as indicated by the rent elasticity of reserves and an interest in exploiting new sources of a resource that become increasingly attractive as the rent increases. S-Resources could easily fall into the category of completely new sources.

Moreover, new resource stocks may become commercially attractive because of technological evolution which can either provide access to hitherto physically unattainable stocks or can act to countervail rising extraction costs. It does not seem unreasonable to expect that the application of existing and evolving technology to S-Resources can make available vast new stocks.

The economics of resource depletion is but one reason for the growing interest in S-Resources. The others are the politics of international power centers, the development of technologies that might render the S-Resources capable of national appropriation and exploitation, the threat of militarization of the ocean bed and space, the desire among the members of the Organization for Economic Cooperation and Development (OECD) to develop
potentially neutral and stable sources of supply and the fear among the
countries of the Group of 77 that they might be excluded from any income
that could flow from the commercial development of S-Resources as indus-
trialized nations use their financial and technological strength to under-
take the economic colonization of what has been designated the "common
heritage of mankind." Moreover, the growing interest of several multi-
national corporations* in S-Resources has excited the suspicions of some
who believe that these organizations are determined to bring within their
profit maximizing ambit the common property of all humanity, and hence
develop them in a socially non-optimal manner.

The deep ocean-bed, an S-Resource that has generated the most in-
terest, illustrates the concerns just cited. The issues pertaining to
the deep ocean bed are discussed next.

**Issues Involved in Deep Seabed Mining**

The military potential of the deep ocean-bed has certainly not es-
caped the attention of writers on naval warfare. Had it not been prevented
by international agreement, then by 1990 there could have been nuclear mis-
siles emplaced on the ocean-bed, permanent observation posts established,
anti-submarine bases constructed and manned torpedo batteries for use a-
against surface shipping devised (Luard, 1974). The occupation of
the seabed for securing military advantage was actively discussed during
the sixties, leading to visions of military confrontation between the super-
powers in yet another arena (Luard, 1974). This was particularly
objectionable because it would involve the subversion of the commonly owned
property of all nations to the strategic aims of two military rivals.

* These firms are the most likely repositories of the capital, management
and technology required to develop S-Resources.
In the area of economic militancy the increasing attempts by producers of raw materials to cartelize world markets for primary goods and the growing dependence of many consumer nations, in particular the United States, Japan and those of Western Europe, on imported oil and minerals have created a desire among many nations of the First World to develop secure and stable sources of supply. It is reasoned that if the sources of supply could be internalized within the industrialized world economic system or if they could be rendered politically neutral, then the hazards of interdependence with the Third World could be mitigated. Deep ocean mining can yield, initially, manganese, cobalt, nickel and copper. Cobalt is a critical strategic mineral and manganese is vital for the steel industry. The very threat of new entry through ocean mining, it has been suggested (Amacher and Sweeney, 1976), could effectively discourage the formation of mineral cartels. The copper cartel, which is just beginning to discover cohesion, would be severely undermined and the monopoly pricing tactics of Zaire and Zambia with respect to cobalt would be rendered very difficult by the development of deep ocean-bed minerals.

The countries of the Group of 77 view the prospects of deep ocean mining with both alarm and excited anticipation. For a very small number of nations that are exporters of cobalt, nickel, copper and manganese, there is the very real prospect of losing market share and export revenues (Wasserman, 1975). The majority of Third World countries, however, conceives of the deep ocean-bed as a cornucopia of mineral wealth. Articles in the popular press (see, for example, Anderson, 1973; and Wertenbaker, 1977) and some early estimates of available minerals published by researchers extrapolated from very limited data (Wright, 1976) have created the illusion of easy riches which many nations of the Third
World fell should accrue to them as a form of rent from a commonly owned resource.*

The first call for formalizing the status of the deep seabed as an S-Resource was made on November 1, 1967 by the Maltese delegate to the U.N., Dr. Arvid Pardo, who presented, in eloquent detail, the economic, environmental, military, and legal interests involved in the oceans and deep seabed. The international response to Dr. Pardo's speech was swift and acrimonious. Almost immediately, the nations of the world found themselves divided and some of those dissensions have yet to be resolved. The Communist states expressed their aversion to establishing a U.N. authority, the Western nations advocated caution and the Latin American countries too warned against any hasty action lest it prejudice any of their extensive claims of territorial seas and continental shelves. Malta, a number of developing countries and Sweden, however, sensed the urgency in declaring the deep ocean-bed an S-Resource (Luard, 1974). At their insistence the U.N. General established an ad hoc committee to study the issue in March of 1968. The work of this committee led to UNCLOS III, whose various conventions have so far failed to produce a treaty.

The technology for developing the deep seabed minerals is the exclusive province of a number of private multinational consortia comprised of corporations domiciled in the U.S., U.K., France, Belgium, W. Germany and Japan.

* M.A. Ajomo does not use the word rent but implies much the same thing when he writes "In other words all states will have a joint interest in the resources of the ocean floor which will entitle them to benefits in the proceeds of exploration even though, in the case of countries of the Third World, they may not be able to contribute pro rata to the costs of exploration and exploitation." "Third World Expectations" in New Directions in the Law of the Sea, Collected Papers - Volume III, ed., Robin Churchill, K.R. Simmonds and Jane Welch, Oceana Publications (Dobbs Ferry, New York: 1973), pp. 307-308.
While mining techniques are fairly well advanced and commercial mining could begin by 1985, the multinational consortia are reluctant to commit large sums to development until the operative rules for the deep ocean have been clarified. UNCLOS III has struggled for several years to define a commercial code for the deep seabed minerals but the traditional suspicions of multinational corporations that many delegates from the Third World harbor, have precluded any final agreement. The multinational corporations, as usual have been limned as voracious entities poised to appropriate for their very private gain the common property of mankind, prevented from doing so only by the ideological alertness of the United Nations. Economic and technological uncertainties, complex enough in the case of nationally appropriate resources, are compounded by legal lacunae in the matter of S-Resources.

It needs to be pointed out that the deep seabed is only a part of the general debate over the oceans. This study does not attempt to focus on all aspects of that debate but rather on those portions of it which pertain to the economic determinants of deep oceanbed minerals development. While the political issues have been extensively discussed by various commentators, the economic question of rent distribution within an international bargaining context has not been explicitly treated.* Perhaps politics will eventually dominate economics in the management of the deep oceanbed, but it is hoped, nonetheless, that an investigation of the economics will provide the outlines of a solution within which the political and institutional questions can be formulated and resolved.

The general debate, does, however, provide a frame of reference for a discussion on deep oceanbed minerals. With reference to deep oceanbed

*-- See, for example, the Proceedings of the Law of the Sea Institute, various years.
minerals the main economic and political components are:

1. The freedom of the major maritime powers to conduct scientific investigations and carry out naval reconnaissance and patrols.

2. The unilateral appropriation of the deep oceans by the major powers.

3. The compulsory transfer of ocean mining technology from the nations of the North to the countries of the South.

4. Quotas on the production of minerals from marine ferroman-ganese deposits to protect the interests of existing net producers, often from the South.

5. Access, largely by the nations of the North to potentially stable sources of important minerals such as copper, cobalt and nickel.

6. The decline of military power as a parameter in the settlement of international disputes and the concomitant rise of economic power (in the form of control over oil and nonfuel minerals) as a source of leverage.

7. The distribution of the benefits from marine minerals development (beyond the 200 mile economic zone) within the general framework of the New Economic Order, entailing a net transfer of resources from the North to the South.

8. The development of manganese nodules through private capital supplied by international mining consortia drawn from Western Europe, Japan and North America or through international public capital controlled by a transnational seabed regime dominated by the Group of 77 and initially funded by the nations of the North and perhaps the Organization of Petroleum Exporting Countries (OPEC).

9. The integration of deep seabed minerals production with a general scheme for commodity price stabilization and international commodity agreements involving producers and consumers.

The issues listed above have to be resolved within the context of international law. The codification of a body of international law for the oceans is proving a monumental task not just because of the complexity of the political questions like delimitation, sovereignty, jurisdiction and enforcement but also because rules governing the economic development of the S-Resources portion of the ocean, the deepsea floor, have to be an integral part of a Law of the Sea.

The legal issues have been divided into over 300 separate articles as embodied in the Informal Composite Negotiating Text of the seventh session of UNCLOS III and agreement has been reached on most issues. The most
significant issue of all, however, the economic development of the deep oceanbed, has eluded a consensus.

The following matters appear largely settled:*

1. Territorial seas will extend up to 12 miles from the coast and with this boundary coastal nations will have complete sovereignty except where limited by international rules of navigation.

2. In straits that are narrower than 24 miles, foreign ships will have almost unrestricted rights of innocent passage on or in international sea lanes.

3. Coastal nations will have economic zones that extend from the 12 mile national limit to 200 miles from the coast. Within the 188 mile economic zone, each coastal state will exercise sovereignty over the mineral and living resources, except for migratory species of fish.

4. The area beyond the 200 mile limit will be international and the resources will be S-Resources.

The following matters have yet to be settled:

1. The rules and institutions that will govern the exploitation of the minerals of the deep oceans.

2. The extent of international prerogatives in enforcing rules on conserving living resources and preventing pollution of the oceans.

3. The priority between coastal and navigational interests when they come into conflict in straits, territorial seas and economic zones.

CHAPTER 2: GAME MODEL FORMULATION

Analysis of the deep oceanbed minerals has either focused on building financial models of hypothetical mining ventures using prices as an exogenous vector (ADL, 1977) or have concentrated on constructing econometric models of various minerals markets and using offshore production as an exogenous variable (Adams, 1975). The bargaining aspect of the problem has usually been abstracted away. The matter of rent distribution needs to be settled in the context of a negotiated outcome between the NP and NC. At the least such an outcome would simultaneously determine world prices and production and have as its basis the relative economic and political bargaining strengths of the actors. The economic strength is assumed to be a function of marginal costs which determine limit prices and consequently, market share, in a price dispute and the political strength is assumed to be a complex, non-quantifiable function of international interdependence and the quest for international egalitarianism. While the combined economic and political bargaining process is not amenable to modeling, the economic aspects by themselves can be rigorously formulated and in investigating the economics some bounds can be established within which a political bargain can be reached. While the economic analysis will not, by itself, provide the solutions, it can help to focus attention to a feasible region within which political debate can be conducted usefully.

To reiterate, the basic economic issues are:

1. How should the rent of production from the deep oceanbed be divided between the NP and the NC in a manner that minimizes conflict, and
2. What will be the prices, production levels, technological royalties and offshore markets shares for cobalt, copper and nickel once commercial ocean mining starts.

In arriving at a solution to the bargaining situation between the NP and the NC the following assumptions will be made:

-- Utility of the NP and NC is a function of rent and the NP and NC maximize rent, and in some cases consumer surplus.

-- The NP and NC are explicitly bound by treaty not to develop the S-Resource without mutual consent.

-- The technology for developing the S-Resource resides only with the NC. It is the availability of technology that confers value on the S-Resource and provides the NC with bargaining strength, thus initiating the game.

-- The cost of developing the S-Resource is not equal to the cost of developing the nationally appropriated resource.

Orthodox economic theory is unable to predict the forms on which agreements might be reached in general situations where settlements must be arrived at by means of explicit or implicit bargainings. All that orthodox economic theory offers is that agreement tends to fall within some range of practicable solutions. Attempts to secure a more precisely defined solution have been made by Hicks (1932), Zeuthen (1930) and Nash (1950, 1953). Nash's theory appears to offer the best framework for solving the bargaining problem regarding ferromanganese nodules.

An important advance made by Nash was the clear distinction between bargaining situations that do and those that do not allow parties a choice among alternative threats by which to bring pressure upon each other. Bargaining situations with one possible threat by each party occur in two cases:

(i) When the two parties can achieve a certain gain by cooperation but when either can threaten to withhold cooperation unless a certain and satisfactory sharing agreement is reached.

(ii) When one or both parties are able to inflict one particular sort of positive damage on the other and use this possibility as a threat.
In both cases agreement means saving the costs of a conflict and this saving can be divided between the two parties.

The bargaining problem has an evident solution in the special case when the situations are completely symmetrical with respect to the two bargaining parties. In this case it seems reasonable to assume that the two actors will share the net gain equally, since neither would be prepared to grant the other better terms than the latter would bestow.

Nash's theory of bargaining (with given threats) is essentially a generalization of this principle for the general case of asymmetric situations. Nash's conclusion is that if the utilities of the two actors are measured by von Neumann-Morgenstern cardinal utility indices, they will reach an agreement at that point within the range of practicable solutions where the product of the utilities each actor ascribes to the net gain (above the conflict situation) is maximized.

Zeuthen also approached the problem of two party bargaining and arrived at a solution mathematically equivalent to that of Nash. Zeuthen's approach is based on a direct analysis of collective bargaining in the labor market but it has general validity for any sort of bargaining situation.

Hicks also sought a solution to the two party bargaining problem by considering collective bargaining in the labor market. Hicks' theory is summarized by Harsanyi (1956) as follows:

"Each bargaining party will make a concession if, in his view, the strike resulting from his refusing this concession would cost him more than the concession would. (Of course, costs must be reckoned at their present values to make significant comparison possible.) The higher a given wage rate the more its acceptance will cost the employer and the longer the strike he will be prepared to endure rather than to accept this wage rate. Thus each wage rate will be
associated in the employer's mind with a strike of given length (with one which would be just as expensive as accepting this wage rate), higher wage rates being associated with longer strikes. On the other hand, the lower a given wage rate the more its acceptance will cost the trade union (in terms of disutility) and the longer the strike they will be prepared to undertake rather than to accept this wage rate. Thus each wage rate will be connected in the trade unionists' minds with a strike of a given length (one which would be just as bad as accepting this wage rate), but in this case lower wage rates will be connected with longer strikes. There will be a unique wage rate that both parties associate with a strike of the same length: this is the highest wage rate that the union can exact from the employer. The latter in effect will not accept a wage rate higher than this one since he knows that his refusal can at worst result only in a strike short enough to cost him less than accepting this wage rate would. On the other hand, for opposite reasons he will certainly be prepared to accept this particular wage rate or, of course, any lower one.

Hicks thus assumes that either party will choose or threaten to choose a strike in preference to a concession only if the strike costs less than the concession. Nash's theory differs in that, according to the theory, each actor is ready to pressure the other by threatening a strike whose actual occurrence, if no agreement can be reached, would in part cost the threatening party more than a concession would, provided the threat is likely to secure better terms from the other actor if agreement succeeds. Nash's assumption is clearly the more reasonable one. Bargainers do use threats of retaliation that would, if enacted, entail losses for themselves no less than for their opponents. It appears rational for them to do this since they can thus attain better terms.

The model formulated below, therefore, relies upon the Nash two-person cooperative game. The general idea of a game, as the term is used here, consists of a sequence of moves to arrive at a conclusion
called a payoff function.

An essential feature of the cooperative game is that binding contracts can be made and utility transferred from one actor to another, though this transfer need not be linear. The utility functions \(R_1\) and \(R_2\), of the two actors can be mapped onto two dimensional Euclidean space. The solution to the game is one that yields a point in the set \(M\) that satisfies both actors. Within \(M\) there is a subset, \(S\), called the feasible set such that given any \((R_1, R_2) \in S\), it is possible for the two actors, in concert, to obtain the utilities \(R_1\) and \(R_2\) respectively. The minimum acceptable payoff is what either could obtain by unilateral action, irrespective of what the other does. This payoff is termed the maximin value of the game for an actor because it is the greatest minimum he/she can obtain by acting alone. If the payoffs are denoted by \(\bar{R}_1\) and \(\bar{R}_2\), then the bargaining game seeks a rule such that a triple \((S, \bar{R}_1, \bar{R}_2)\) has a solution:

\[
\emptyset (S, \bar{R}_1, \bar{R}_2) = (R_1^*, R_2^*)
\]

A measure of the bargaining power of the two actors is clearly needed and it was to address this problem that Nash introduced the concept of a threat point which is the outcome that would result if negotiations failed and non-cooperation ensued. The threat point is the solution to a Nash non-cooperative game and is the minimum payoff either actor would accept in the event of non-cooperation. There is no rational reason for either player to accept less.
Nash's premise is that actors enter into a bargaining game because they expect to attain payoffs larger than those given by the threat point. The actors perceive incremental gains accruing from cooperation and proceed to divide these gains in a manner directly proportional to the losses that might be sustained if negotiations broke down. The relative bargaining power of either actor is, therefore, a function of his/her ability to inflict losses on the other.

Nash proceeded to solve the game by first postulating a set of six axioms and then demonstrating that the axioms were uniquely satisfied by a point on the bargaining set. This point, according to the axioms, is pareto-optimal and is given by maximizing the product of \( (R_2^* - R_2^0) \) and \( (R_1^* - R_1^0) \).

The six axioms of John Nash are:

\( A1: \) The actors are rational.
\( (R_1^*, R_2^*) \geq (R_1^0, R_2^0) \)

\( A2: \) The solution is feasible.
\( (R_1^*, R_2^*) \in S \)
A3: The solution is pareto-optimal.

If \((R_1, R_2) \in S\), and \((R^*_1, R^*_2) \geq (R_1, R_2)\) then
\((R_1, R_2) = (R^*_1, R^*_2)\)

A4: The solution is independent of irrelevant alternatives.

If \((R^*_1, R^*_2) \in S\) and \((R^*_1, R^*_2) = \emptyset(S, R^*_1, R^*_2)\), then
\((R^*_1, R^*_2) = \emptyset(S, R^*_1, R^*_2)\)

This implies that the feasible set is enlarged from \(S\) to \(S\), the solution to the new problem will be either \((R^*_1, R^*_2)\) itself or a new point in the bigger set \(S\), not a point in the old set \(S\).

A5: The solution is independent of linear transformations.

\[ R_1 = a_1 R_1 + b_1 \]
\[ R_2 = a_2 R_2 + b_2 \]

Then if \(\emptyset(S, R^*_1, R^*_2) = (R^*_1, R^*_2)\) it must be that \(\emptyset(S, a_1 R_1 + b_1, a_2 R_2 + b_2) = (a_1 R^*_1 + b_1, a_2 R^*_2 + b_2)\)

A6: The solution is symmetrical. Suppose \(S\) is such that

\((R_1, R_2) \in S \iff (R_2, R_1) \in S\).

Suppose also \(R^*_1 = R^*_2\) and \(\emptyset(S, R^*_1, R^*_2) = (R^*_1, R^*_2)\) then
\(R^*_1 = R^*_2\).

THE GAME MODEL

A bewildering variety of institutional arrangements have been proposed to deal with the question of how the development of ferromanganese nodules should proceed. At one end of a spectrum are rather simple schemes where an attempt would be made to determine some level of output from offshore mining and the world price of the products. A rather more complicated scheme would envision the NC (or the mining consortia within the NC) transferring their technology to the NP so that current
onshore producers would have the option to mine the deep seabed.

A rather more involved version of the previous scheme would have not only the NC transferring technology but also paying some form of production royalties (on offshore mining) to the NP. Variants of these three schemes have been discussed for several years by delegates from 148 countries at UNCLC; III since 1968.

In an attempt to model the essential economic elements of the various institutional schemes that have been propounded, the game developed in this section will be played under three basic scenarios. The first scenario is one in which only the NC develop the ocean minerals and the policy variables are price and world demand share of either actor. In the second scenario the NC, which are assumed to possess the technology for developing the ferromanganese nodules, license it to the NP at a royalty rate which is a function of the price and only the NP produce. In this scenario world demand is met from nationally appropriated onshore mines and deep oceanbed mines and the policy variables are the output share of offshore production, the price and the technology licensing royalty.

In the third scenario, the NC license technology to the NP, the NP charge the NC a production royalty which is a function of price and both produce. The policy variables are price, demand share of NP and NC, output share of offshore production, technology and production royalties.

The quantification of the game model is next discussed. For purposes of exposition the model is first developed with a static formulation where ocean minerals are considered a single resource. A dynamic version of the model is next presented. Finally, a static joint product model for scenario 1 is developed to illustrate how the basic
game model can be extended to incorporate the coproduct aspect of the problem. The discussion starts with an analysis of the static symmetrical case.

Model Specification

\[ P = \text{world price of the resource} \]

\[ D(P) = D = \text{net world demand for the resource, i.e. the foreign demand facing the NP} \]

\[ D(P) = AP^{-b} \text{ (isoelastic demand curve), where A and b are constants; b is the price elasticity of net demand, or, alternatively,} \]

\[ D(P) = a-bP \text{ (linear demand curve)} \]

\[ R_{NP} = \text{rent accruing to the NP} \]

\[ R^0_{NP} = \text{threat point of the NP} \]

\[ R_{NC} = \text{rent accruing to the NC} \]

\[ R^0_{NC} = \text{threat point of the NC} \]

\[ C_S = \text{cost of producing one unit of the S-Resource} \]

\[ C_p = \text{cost of producing one unit of the nationally appropriated resource, i.e. the cost to the NP} \]

The Symmetrical Case

The complexities of the economic bargaining problem owe their origins to the different cost curves facing the NP and NC and the different threat points for either. If both faced the same costs and the threat points were identical then the solution would be trivial. The problem would be reduced to that of a two member cartel which sets a monopoly price and divides the rent equally. This is demonstrated below using a linear demand curve \((D = a-bP)\).

The Nash Solution is obtained by:

\[
\max_{P, B} R = (R_{NP} - R^0_{NP})(R_{NC} - R^0_{NC})
\]
where $B = \text{fraction of world demand met by NP}$. Since $R_{NP}^o = R_{NC}^o$, a suitable choice of axes can set both equal to zero. Further, $C_S = C_p = C = \text{cost of producing one unit of the resource}$.

So that, $\text{Max } R = R_{NP}^o R_{NC}^o$

$$= [(P-C)BD] [(P-C) (1-B)D]$$

$$= (P-C)^2 D^2 B(1-B)$$

$$\frac{\partial R}{\partial P} = [2 (P-C)D^2 + 2D \frac{dD}{dP} (P-C)^2] B (1-B)$$

$$= 0$$

$$\frac{dD}{dP} = -b; \text{ substituting in the equation above leads to}$$

$$0 = 2(P-C) D^2 - 2(P-C) Db \text{ or } P = \frac{D + C}{D}$$

Substituting for $D$

$$P = \frac{a + bC}{2b}$$

$$\frac{\partial R}{\partial B} = 0 = (P-C)^2 D^2 (1-2B) \text{ or } B = \frac{1}{2}$$

The Nash Solution states that the NP and NC divide the world demand market equally at a price, $P = \frac{a + bC}{2b}$.

If there were a monopolist in control of the resource, then that rent would be

$$R = (P-C) (a-bP)$$

$$= -bP^2 + P(bC + a) - aC$$

Maximizing rent:
\[
\frac{dR}{dP} = 0 = -2Pb + bC + a
\]

so that \( P = \frac{a + bC}{2b} \).

Thus, the monopoly solution is the same as the Nash Solution.

The Static Model

Scenario 1: Both NP and NC produce; no transfer payments

The NC can, of course, produce only from the S-Resource and the NP from only the nationally appropriated resource since they do not possess the technology to develop the S-Resource. Both can produce as much as they choose.

The objective function of the NP is:

\[
R_{NP} = (P - C_P)BD
\]

\( 0 \leq B \leq 1 \)

where \( B \) = fraction of world demand met by NP.

The objective function of the NC is:

\[
R_{NC} = (P - C_S)(1 - B)D
\]

The policy variables in this scenario are \( P \) and \( B \). The game solution is obtained by maximizing the following function:

\[
\text{Max } R = (R_{NP} - R_{NP}^*) (R_{NC} - R_{NC}^*)
\]

Scenario 2: Only NP produce, transfer payment from NP to NC

In this scenario, the NC license their technology to the NP and only the NP produce. It is equivalent to the NC also producing and transferring the rent to the NP after deducting a technology royalty. The royalty on technology, \( Q \), is considered to be a fraction of the price \( P \).

The objective function of the NP is:

\[
R_{NP} = (P - C_P)(1 - \gamma)D + (P(1 - Q) - C_S) \gamma D
\]
where $\gamma = \text{output share of S-Resources}$.

The objective function of the NC is:

$$R_{NC} = Q\gamma D$$

The policy variables are $P$, $Q$, $\gamma$. The game solution is obtained by solving:

$$\max R = (R_{NP}^\circ - R_{NP}^\star)(R_{NC}^\circ - R_{NC}^\star).$$

Scenario 3: Both NP and NC produce; transfer payments

In this scenario, both the NP and NC produce; the NC license technology to the NP and the NP charge the NC a production royalty, $Z$ (which is considered a fraction of price, $P$) for producing from the S-Resources.

The objective function of the NP is:

$$R_{NP}^\circ = (P-C_P)(1-\gamma)D + (P(1-Q) - C_S)\gamma\Theta D + PZ(1-\Theta)D$$

$$0 \leq Z \leq 1$$

where, $\gamma = \text{output share of S-Resources}$

$\Theta = \text{production share of S-Resources allocated to the NP}$.

The objective function of the NC is:

$$R_{NC} = (P(1-Z) - C_S)(1-\Theta)\gamma D$$

$$+ P\Theta\gamma D$$

The policy variables are $P$, $Q$, $Z$, $\gamma, \Theta$.

The game solution is obtained by solving:

$$\max R = (R_{NP}^\circ - R_{NP}^\star)(R_{NC}^\circ - R_{NC}^\star).$$
The Dynamic Model

Scenario 1: Both NP and NC produce; no transfer payments

Since the resource is depletable, costs will be a function of reserves in each time period and the rent will be the discounted sum of revenues over the time horizon, T.*

If the reserves of the nationally appropriated resource at time \( t - 1 \) are \( F_{t-1}^P \) and those of the S-Resource are \( F_{t-1}^S \), then at time \( t \),

\[
F_t^P = F_{t-1}^P - B_t D_t \\
F_t^S = F_{t-1}^S - (1 - B_t) D_t
\]

where \( D_t = D_t(P_t) = (a - b P_t)(1+g)^t \) (using a linear demand curve)

where \( g = \) annual rate of growth of demand.

The cost of producing from nationally appropriated resources at time \( t \)

\[
W_t = \frac{P}{F_t^P}
\]

is \( P \) where \( W_t \) is a constant equal to the production cost of the initial time multiplied by the reserves at that time. Production costs rise hyperbolically as reserves are depleted and this specification captures that phenomenon.

The cost of producing from the S-Resource at time \( t \), is \( \frac{W_2}{F_t} \) where \( W_2 \) is a constant.

The objective function of the NP is:

\[
R_{NP} = \int_{0}^{T} e^{-\delta_1 t} \left[ P_t - \frac{W_1}{F_t} \right] B_t D_t \, dt
\]

where \( \delta_1 = \) discount rate for the NP.

The objective function of the NC is:

\[
R_{NC} = \int_{0}^{T} e^{-\delta_2 t} \left[ P_t - \frac{W_2}{F_t} \right] (1-B_t) D_t \, dt
\]

where \( \delta_2 = \) discount rate for the NC. The game is solved in the usual manner and like the two scenarios following, has the characteristics of a problem in optimal control. The policy variables are \( P_t, B_t \).

Scenario 2: **Only the NP produce; transfer payment from NP to NC**

Following the logic indicated above,

\[
P_t^P = P_{t-1}^P - (1-\gamma_t) D_t
\]

\[
F_t^S = F_{t-1}^S - \gamma_t D_t
\]

where \( \gamma_t = \) output share of the S-Resource. The objective function of the NP is:

\[
\text{Max } R_{NP} = \int_{0}^{T} e^{-\delta_1} \left[ (P_t - \frac{W_2}{0.5F_t}) (1-\gamma_t) D_t + (P_t(1-Q) - \frac{W_2}{0.5F_t} \gamma_t D_t) \right] dt
\]

and the objective function of the NC is:
\( \text{Max } R_{\text{NC}} = \int_0^T e^{-\delta t} [P_t Q + D_t] dt \)

The policy variables are \( P_t, \gamma_t, Q \).

The game is solved in the usual manner.

Scenario 3: Both NP and NC produce; transfer payments

The objective function of the NP is:

\[
R_{\text{NP}} = \int_0^T e^{-\delta t} \left[ \left( P_t - \frac{1}{\prod_t} \right) (1-\gamma_t) D_t + (P_t(1-Q) - \frac{W}{F} \gamma_t B_t D_t + P_t Z (1-B_t) \gamma_t D_t) \right] dt
\]

where \( \prod_t = \prod_{t-1} (1-\gamma_t) D_t \)

\[
\prod_t = \prod_{t-1} - \gamma_t D_t
\]

The objective function of the NC is:

\[
R_{\text{NC}} = \int_0^T e^{-\delta t} \left[ \left( P_t(1-Z) - \frac{W}{S} \gamma_t B_t D_t + P_t Q \gamma_t B_t D_t \right) \right] dt
\]

The policy variables are \( P_t, Q, Z, \gamma_t, B_t \). The game is solved in the usual manner.
The discussion so far has related to a single product resource. In order to develop a more realistic formulation of the ocean mining problem the model is extended to a joint product resource in the next section. Since the extension is rather direct only a static version of scenario 1 is presented. Other scenarios can be developed in a similar fashion and are indeed explored in some detail in Chapter 4.

The Bargaining Model for a Joint Product Resource

The ferromanganese deposits on the oceanbed can be considered as a resource that is a joint product of cobalt, nickel, copper and manganese. The greatest commercial interest is in extracting cobalt and nickel, with some interest in copper and very little in manganese. Indeed, ocean mining has often been characterized as a nickel winning operation. U.S. Steel Corporation has expressed some concern about securing long term supplies of manganese from onshore mines and is of the view that around the turn of the century, ocean minerals might be a source of manganese for the steel industry. However, the first generation of ocean mining ventures will probably not extract manganese owing to its low price, high marginal costs and relative abundance on land with little likelihood of a producer's cartel in the foreseeable future.
The Net Producers (NP) as before are those nations that produce more than they consume. The Net Consumers (NC) are those countries that consume more than they produce. The NC expect to secure some of the rents of production by exploiting marine ferromanganese deposits through the various ocean mining consortia that have been formed.

Let

\[ P_1 = \text{world price of cobalt} \]
\[ P_2 = \text{world price of nickel} \]
\[ P_3 = \text{world price of copper} \]
\[ C_{P1} = \text{marginal cost of production of NP for cobalt} \]
\[ C_{C1} = \text{marginal cost of production of ocean-based cobalt} \]
\[ C_{P2} = \text{marginal cost of production of NP for nickel} \]
\[ C_{C2} = \text{marginal cost of production of ocean-based nickel} \]
\[ C_{P3} = \text{marginal cost of production of NP for copper} \]
\[ C_{C3} = \text{marginal cost of production of ocean-based copper} \]
\[ R_{NC} = \text{rents of the NC} \]
\[ R_{NP} = \text{rents of the NP} \]
\[ R_{NC}^* = \text{threat point of the NC} \]
\[ R_{NP}^* = \text{threat point of the NP} \]
\[ D(P_1) = \text{net demand for cobalt} \]
\[ D(P_2) = \text{net demand for nickel} \]
\[ D(P_3) = \text{net demand for copper} \]

Scenario 1: Both NP and NC produce; no transfer payments

In this scenario, the game consists of \( P_1, P_2, P_3 \), world prices for minerals and \( B_1, B_2, B_3 \), the world market shares of the NP.
\[
R_{NC} = (P_1 - C_{C1}) D (P_1) (1-B_1) + (P_2 - C_{C2}) D (P_2) (1-B_2) + \\
(P_3 - C_{C3}) D (P_3) (1-B_3)
\]

\[
R_{NP} = (P_1 - C_{P1}) D (P_1) B_1 + (P_2 - C_{P2}) D (P_2) B_2 + (P_3 - C_{P3}) D (P_3) B_3
\]

The objective function of the game is:
\[
R_{NP}^\circ = (C_{C1} - C_{P1}) D (C_{C1}) + (C_{C2} - C_{P2}) D (C_{C2}) + (C_{C3} - C_{P3}) D (C_{C3})
\]

\[
R_{NC}^\circ = 0
\]

\[
0 \leq B_1, B_2, B_3 \leq 1
\]

\[
\text{MaxR} = (R_{NP} - R_{NP}^\circ) (R_{NC} - R_{NC}^\circ)
\]

\[
P_1, P_2, P_3, B_1, B_2, B_3
\]

The policy variables are \(P_1, P_2, P_3\) and \(B_1, B_2, B_3\).

The demand curves and production costs necessary to simulate the model are derived in the next chapter.
CHAPTER 3: DEMAND CURVES AND PRODUCTION COSTS

The implementation of the game model requires the specification of demand curves and data on production costs from onshore and offshore mining. In the section below the demand curves facing the NP for cobalt, nickel and copper are first formulated. Offshore and onshore production costs for the three minerals are next presented.

NET DEMAND CURVES FOR COBALT, NICKEL AND COPPER

The Demand Curve Facing the NP for Cobalt

In terms of mined output, the major non-communist bloc producers of cobalt in 1975 were Zaire (53%), Zambia (9%), Australia (7%), Morocco (6%), and New Caledonia (6%). In 1975, the major producers of the metal in terms of refined output were Zaire (65%), Zambia (9%), Norway (4%), Canada (4%), and Finland (4%). Belgium is another major producer of the refined metal but does not publish statistics on output. (Sibley, 1977). Zaire exports its output chiefly to Belgium and the U.S., Zambia exports mainly to the U.K., Japan, and the U.S., and Morocco exports to France and the People's Republic of China. Botswana exports its ore to the U.S. for refining, the Philippines exports its ore to Japan for refining and some Australian ore is sent to Canada for refining.

The United States is the most important consumer of cobalt, and U.S. demand accounts for about one-third of the non-communist production of the resource. A source of supply for domestic users is the General Services Administration (GSA) which periodically releases cobalt from its strategic stockpile. The GSA has a three year supply on hand. The principal sources of supply for the U.S. in 1976 were Zaire (41%), Belgium (15%), Zambia (11%),
Norway (7%), and Botswana (6%) (Sibley, 1977, p. 9).

Econometric analysis of the world cobalt market (CRA*, 1976, Burrows, 1971) indicates that the industry has the characteristics of a monopolist with a competitive fringe. Zaire, the chief supplier, acts as the price setter. It selects a point on the net average revenue curve such that it maximizes profit. Alternatively, these studies suggest, Zaire maximizes foreign exchange earnings rather than total profit, but this policy would not move it far from the monopoly point. The competitive fringe, of course, acts as price takers and is mostly composed of Canada, Australia, Finland, Morocco, Zambia, Botswana, Norway and New Caledonia. The African producers of cobalt accounted for 74% of the refined output in 1976 and a cartel with Zaire as its core would be easy to form.

The price elasticity of demand for cobalt has been estimated at -1.7 while the elasticity of net demand facing Zaire, the price setter (the world price of cobalt is set by Societe Zairaise de Commercialization (SOZACOM), the marketing subsidiary of GECAMINES of Zaire), has been calculated at -2.55 (* Charles River Associates (CRA), 1976).

The elasticity estimates were based on a price range from $12.2/Kg to $7.9/Kg (in 1975 dollars) and conducted over a 20-year time series, from 1953 to 1973. This elasticity will be used to derive a simplified demand equation for cobalt for use in the game model.

Assume that the demand curve is of the form,

\[ D = A p^{-b} y^c \]  \hspace{1cm} (3.1)

where

\[ D = \text{demand} \]
\[ A, b, c = \text{constants} \]
\[ P = \text{real price} \]
Y = index of industrial production

By normalizing Y in 1975, i.e., setting Y equal to 1, equation 3.1 reduces to

\[ D = A p^{-b} \] (3.2)

In 1975, the demand facing the NP was 19.14 \times 10^6 kilograms of metal output. The world price for cobalt in 1975 was $8.8 per kilogram. Substituting the values of D, P and b, which is the price elasticity of demand in equation 2, leads to

\[ 19.14 \times 10^6 = A(8.8)^{-1.7} \]

or \( A = 7.82 \times 10^8 \)

The static demand formulation then becomes

\[ D = 7.82 \times 10^8 p^{-1.7} \] (3.3)

The lower bound for P is determined by the marginal cost of NC and the upper bound, in theory, by setting demand equal to zero. However, since the elasticity was estimated with an upper bound of \( P = $12.2/\text{Kg} \) it may not be desirable to go much beyond this price and still retain the form of equation 4 since almost nothing is known about the behavior of the cobalt market at very high prices. Hence, an upper bound of \( P = $20/\text{Kg} \) is chosen, somewhat arbitrarily. The marginal cost of the NC is $5.1/\text{Kg}. (See Table 3.3)

**The Demand Curve Facing the NP for Nickel**

The major NP for nickel are Canada, the Dominican Republic, Guatemala, Australia, New Caledonia, Indonesia, Philippines, Rhodesia and South Africa.

The NP face a net demand curve which is the demand curve for imports by the NC. An econometric attempt at estimating this demand curve did not
lead to results with significant t-statistics. The long run elasticity of demand for the output of the NP is probably greater than -1.0 because substitutes for nickel are available in virtually all of its uses. Cobalt, manganese and copper are important alternates to nickel, although the costs of substitution are not inconsiderable. Since nickel is highly substitutable in the long run, especially with cobalt, a long run price elasticity of net demand equal to that of cobalt has been selected, i.e. 1.7.

As in the case of cobalt, the demand curve facing the NP is assumed to have the form
\[ D = A p^{-b} Y^c \]  
(3.4)

where the symbols have the meanings indicated earlier.

Since only a static formulation of the net demand curve is contemplated, \( Y \), which is an index, can be set equal to 1 in 1975 and the demand curve reduced to the familiar form
\[ D = A p^{-b} . \]  
(3.5)

\( b \), which is the price elasticity of demand for the output of the NP, is -1.7.

Table 3.1 shows the world price and demand facing the NP from 1967 to 1975.

Substituting the 1975 values of metal demand and price in equation 5 leads to
\[ 604.5 \times 10.6 = A(4.466)^{-1.7} \]

or \( A = 7.696 \times 10^9 \).

The specification for the net demand curve becomes
\[ D = 7.696 \times 10^9 p^{-1.7} . \]  
(3.6)
The upper bound for price is taken to be $15/Kg and the lower bound is the marginal cost of production from ocean mining, which is $1.9/Kg. (See Table 3.3) These bounds are selected on the same basis as described for cobalt.

### TABLE 3.1

<table>
<thead>
<tr>
<th>Year</th>
<th>Net Demand $x10^6$ Kg</th>
<th>Price $$/Kg (constant 1975 $$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>301.1</td>
<td>3.322</td>
</tr>
<tr>
<td>1968</td>
<td>339.0</td>
<td>4.498</td>
</tr>
<tr>
<td>1969</td>
<td>315.2</td>
<td>4.136</td>
</tr>
<tr>
<td>1970</td>
<td>451.6</td>
<td>3.916</td>
</tr>
<tr>
<td>1971</td>
<td>447.2</td>
<td>3.872</td>
</tr>
<tr>
<td>1972</td>
<td>455.6</td>
<td>3.916</td>
</tr>
<tr>
<td>1973</td>
<td>513.6</td>
<td>4.048</td>
</tr>
<tr>
<td>1974</td>
<td>559.0</td>
<td>4.180</td>
</tr>
<tr>
<td>1975</td>
<td>604.5</td>
<td>4.466</td>
</tr>
</tbody>
</table>

Source:  
2 Computed from data in Nickel - 1977, op. cit., Table 7.
The Demand Curve Facing the NP for Copper

The major non-communist exporters of copper are Canada, Chile, the Philippines, South Africa, Australia, Zambia and Zaire. Table 3.2 shows the demand met by the NP from 1967 to 1975, together with the U.S. producer's price and the London Metals Exchange (LME) price for those years.

Following the custom adopted for cobalt and nickel, the net demand curve facing the NP is assumed to have the static form

$$D = AP^{-b}.$$  \hspace{1cm} (3.7)

A recent analysis of the world copper market was conducted by Charles River Associates. Their study revealed that the U.S. had a long-run price elasticity of demand of -0.48 while the rest of the non-communist world had a long-run price elasticity of demand of -0.15. Since the U.S. accounts for 33.4% of the non-communist demand, according to the study, the weighted average world long-run price elasticity is 

$$-0.48 \times 0.334 + -0.15 \times 0.666 = -0.26.$$  

The U.S. elasticity of supply was shown in the same study to be 0.61 and that of the other NC to be 4.14. The U.S. accounts for 25% of world production and the other NC for about 10%. The weighted average price elasticity of supply for the NC is

$$\frac{25}{35} \times 0.61 + \frac{10}{35} \times 4.14 = 1.62$$

The elasticity of net demand or the demand facing the NP can be estimated from the elasticity of total demand and elasticity of supply for the NC.

Let

$$T = \text{total demand}$$
$$N = \text{net demand, i.e. demand facing NP}$$
$$S = \text{supply from the NC}$$
\[ \eta_T = \text{price elasticity of total demand} \]
\[ \eta_N = \text{price elasticity of net demand} \]
\[ \eta_S = \text{price elasticity of NC supply} \]

**TABLE 3.2**

<table>
<thead>
<tr>
<th>Year</th>
<th>Demand facing $1 \text{NP} \times 10^6 \text{Kg}</th>
<th>US Producer $2 \text{Price} $/\text{Kg}</th>
<th>L.M.E. Price $3 $/\text{Kg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>2680.2</td>
<td>1.37</td>
<td>1.83</td>
</tr>
<tr>
<td>1968</td>
<td>2797.4</td>
<td>1.43</td>
<td>1.90</td>
</tr>
<tr>
<td>1969</td>
<td>2918.1</td>
<td>1.55</td>
<td>2.15</td>
</tr>
<tr>
<td>1970</td>
<td>3026.9</td>
<td>1.78</td>
<td>1.96</td>
</tr>
<tr>
<td>1971</td>
<td>3175.3</td>
<td>1.52</td>
<td>1.43</td>
</tr>
<tr>
<td>1972</td>
<td>3502.6</td>
<td>1.43</td>
<td>1.35</td>
</tr>
<tr>
<td>1973</td>
<td>3781.2</td>
<td>1.58</td>
<td>2.16</td>
</tr>
<tr>
<td>1974</td>
<td>4017.3</td>
<td>1.86</td>
<td>2.24</td>
</tr>
<tr>
<td>1975</td>
<td>4072.7</td>
<td>1.41</td>
<td>1.23</td>
</tr>
</tbody>
</table>


Clearly,
\[ N = T - S \]  \hspace{1cm} (3.8)

The NP meet the residual demand of the NC.

Suppose \( N \) is a fraction, \( F \), of \( T \). Then,
\[ N = FT \]
\[ S = (1-F)T \]

Taking derivatives with respect to price, \( P \), in equation (3.8) results in

\[ \frac{dN}{dP} = \frac{dT}{dP} - \frac{dS}{dP} \]  \hspace{1cm} (3.9)

Multiplying equation (3.9) by \( \frac{P}{T} \),

\[ \frac{dN}{dP} \frac{P}{T} = \frac{dT}{dP} \frac{P}{T} - \frac{dS}{dP} \frac{P}{T} \]

or

\[ F \frac{dN}{dP} \frac{P}{N} = \frac{dT}{dP} \frac{P}{T} - (1-F) \frac{dS}{dP} \frac{P}{S} \]

But,

\[ \frac{dN}{dP} \frac{P}{N} = \eta_N , \quad \frac{dT}{dP} \frac{P}{T} = \eta_T \]

and,

\[ \frac{dS}{dP} \frac{P}{S} = \eta_S \]

so that,

\[ F \eta_N = \eta_T - (1-F) \eta_S \]

or

\[ \eta_N = \frac{\eta_T}{F} - \frac{1-F}{F} \eta_S \]  \hspace{1cm} (3.10)
The NP account for 60% of the NC total demand market, so that \( f = 0.60 \). Substituting the values of \( n_T \) and \( n_S \) in (3.10) yields the value of \( n_N = -1.48 \).

The demand curve facing the NP for copper can now be obtained. The world price for copper in 1975 was unusually low, being $1.23/Kg compared with an average of $1.8/Kg for 1967 to 1975. Substituting the latter price and the 1975 net demand for copper in equation (3.7),

\[
4072.7 \times 10^6 = A (1.8)^{-1.48}
\]

or

\[
A = 97.2 \times 10^8
\]

The net demand curve facing the NP is

\[
D = 97.2 \times 10^8 \ p^{-1.48}
\]  

(3.11)

The upper limit for the price in this formulation is set at $8/Kg and the lower limit at $1.23 which is the lowest price attained by copper on the London Metals Exchange during the period 1967 to 1975. The upper bound is the price at which the demand for copper is substantially reduced in the long run. Normally, the lower bound for the price would have been the marginal cost of production from ocean mining, but in the case of copper this is $1.5/Kg (see Table 3.3), which is higher than $1.23/Kg that was the price quoted on the London Metals Exchange in 1975 and also higher than the $1.41/Kg which was the U.S. producer's price in 1975.

COSTS OF OFFSHORE PRODUCTION

The components of cost involved in deep ocean mining are (i) pre-operational costs consisting of research and development, exploration
and prospecting, capital equipment for mining, transportation and processing and (ii) operational costs related to energy, labor materials, insurance and general administration incurred while mining, transporting and processing the ferromanganese deposits.

On the basis of research being conducted at M.I.T., it appears that the pre-operational costs will be around $186 million per million metric tons of processing capacity for a hypothetical deep ocean mining venture.* The operating costs before capital changes might be $17.1 million per million tons of recovered nodules. The M.I.T. group has assumed a cost of debt of 10%. This appears low considering the risk class of the investment. The risks relate to technological, business, political, legal and environmental factors. It seems reasonable to expect that a risk premium should be added. A premium of 3.5% is assumed in the analysis that follows. A 13.5% capital change is close to the minimum that analysts from a U.S. mining company and a high technology firm, both closely involved in ocean mining consortia, have indicated would be applicable. The cost of capital charge,** the allocations of pre-operations capital spending over the life

---

* The research group has been led by Professor J.D. Nyhart and has included Lance Antrim and Arthur Capstaff. A document that summarizes much of the work is J.D. Nyhart, et al, A Cost Model of Deep Ocean Mining and Associated Regulatory Issues, M.I.T., Sea Grant Program, MITSG 78-4, M.I.T., (Cambridge, MA, March 1978.)

** This charge is in the form of interest on debt. Representatives from British Petroleum, Deepsea Ventures and Westinghouse Corporation, among others, have voiced the concern that even this expensive debt may be very difficult to obtain if there are any legal risks associated with the venture. These observations were noted at a workshop sponsored by the M.I.T. Sea Grant at M.I.T. on April 6, 1978. It might be mentioned that these same representatives indicated that when undertaking a financial analysis of deep ocean mining, the hurdle internal rate of return (IROR) would have to be around 18% to 20%. This is in IROR unadjusted for legal or political risk.
of the ocean mining venture (taken to be 20 years in defining a mine site) and the operating costs together yield a figure of $51.41 per metric ton on harvested nodules. This is the cost of producing the joint product resource from the deep oceanbed.

Since no manganese will be recovered, at least by the first generation consortia, this cost must be distributed among cobalt, copper and nickel.

It is expected that mining and transporting might account for 40% of the cost and processing for the rent. While mining and transportation can be allocated on the basis of abundance, processing cannot because the costs associated with it are not directly proportional to abundance. Cobalt is the most difficult to process, followed by nickel and then by copper. Some industry and consulting sources feel that on an average, processing costs will be distributed in the following approximate manner: cobalt, 28%; copper, 25%; nickel, 47%.*

Processing will probably account for 60% of costs, and mining and transportation for the rest. Consequently, mining and transportation account for $20.56 per ton and processing for $30.84 per ton. On the basis of an abundance of 0.2% for cobalt, 1.1% for copper and 1.3% for nickel, the mining and transportation costs are $1.6 for cobalt, $8.7 for copper and $10.3 for nickel. The processing costs of $30.84 are allocated on the basis of the costs distribution mentioned earlier and are $8.6 for cobalt, $7.8 for copper and $14.40 for nickel. As Table 3.3 indicates, these figures imply a cost per kilogram of $5.1 for cobalt, $1.9 for nickel and $1.5 for copper.

* The names of the sources and their organizational affiliations are withheld on request. The distribution of costs takes into account both abundance and extractive difficulty.
TABLE 3.3
Costs of Production for Ocean Mining

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Abundance Kg/M.T.</th>
<th>Mining and Transportation Costs</th>
<th>Processing Costs</th>
<th>Costs Per Kilogram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>2</td>
<td>$1.6</td>
<td>$8.6</td>
<td>$5.1</td>
</tr>
<tr>
<td>Copper</td>
<td>11</td>
<td>$8.7</td>
<td>$7.8</td>
<td>$1.5</td>
</tr>
<tr>
<td>Nickel</td>
<td>13</td>
<td>$10.3</td>
<td>$14.4</td>
<td>$1.9</td>
</tr>
</tbody>
</table>

A comparison of the costs of producing from onshore and offshore mines is presented in Table 3.4.

TABLE 3.4
Marginal Costs of Production for NP and Ocean Mining Operations (Figures in $/Kg)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Marginal Cost of Production, NP</th>
<th>Ocean Mining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>4.3</td>
<td>5.1</td>
</tr>
<tr>
<td>Copper</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Notes: The marginal cost of producing from onshore mines was obtained as follows: For cobalt -- Charles River Associates, Cartelization in the World Cobalt Market: Economic Analysis and Policy Implications, Cambridge, MA, August 1976.


CHAPTER 4: MODEL RESULTS AND CONCLUSIONS

The game theoretic model developed in Chapter 2 is applied here to marine ferromanganese minerals.* There are essentially two purposes to the exercise:

(i) To explore the distribution of rents between the NP and the NC and the composition of these rents in terms of prices, market shares, output shares from deep ocean mining, and royalties on technology and production, if any.

(ii) To examine the impact of linking minerals in a joint commodity agreement when the markets for these minerals are of vastly different sizes. It is worth noting perhaps that cobalt is a high priced mineral with a small market, nickel is a medium priced mineral with a medium market, and copper is a relatively low priced mineral with a large market.

Specifically, it is of interest to

(a) Analyze what happens to the world cobalt** market when cobalt, nickel and copper are made the subject of an international joint commodity agreement, and

(b) What happens to the prices of the three minerals when they are produced from a joint product resource. This resource yields cobalt, nickel and copper in proportions which are very different from the proportions of the net world demand markets for these minerals.

In this chapter the static scenarios only will be analyzed since the static analysis captures most of the features of interest. A dynamic form-

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* In practice, the NP and NC will play a game with incomplete information or an I-game. In such an event the actors will assign subjective probability distributions over some space of payoff functions. If the subjective probability distributions satisfy a certain mutual consistancy requirement then any given I-game, G, will be equivalent to a certain game with complete information, called the "Bayes-equivalent" G* of G. It has been shown by John C. Harsanyi that any Nash equilibrium point of this Bayesian game yields a "Bayesian equilibrium point" for the original game and conversely. The equilibrium will be unique and in the manner of Nash, pareto-optimal. For proof of this see "Games with Incomplete Information Played by 'Bayesian' Players. Part II. Bayesian Equilibrium Points," Management Science, Vol. 14, No. 5, Jan. 1968.

** It is anticipated that the greatest impact of deep seabed mining will be on the international market for cobalt.
ulation of the model is presented in Appendix 2, but because of its computational complexity, it is not solved. It is expected, however, that the solution to the static cases will be of a validity that permits general conclusions about the economics and management of deep ocean mineral resources.

In the sections that follow the threat point outcomes are first determined, the three scenarios discussed in Chapter 2 are analyzed, and finally, conclusions based on model results are presented.

The Threat Point Outcomes

The threat point solutions to the games need to be determined before the bargaining model can be applied, since the cooperative solution depends on the threat point.

Since the threat point is a non-cooperative outcome, it is a simple matter to calculate the rents to the NP and NC at this point. The NP prevent market entry by the NC by setting a limit price that reduces the rents of the NC to zero. This price is clearly the marginal cost of the NC. There is no need to set a limit price below this. Since the marginal costs of the NP are lower than that of the NC, the former still reap a positive rent, though it might be expected that this rent would be lower than that ensuing from cooperation. If it was not, there would be no incentive to negotiate.

For cobalt the threat point rent is

$$ R_{NC}^0 = 0, R_{NP}^0 = (5.1-4.3) \times 10^8 (5.1)^{-1.7} = \$39.2 \times 10^6 . $$

This is obtained by calculating the demand at the limit price and multiplying this by the rent per unit of demand.

For nickel, the threat point rent is

$$ R_{NC}^0 = 0, R_{NP}^0 = (1.9-1.6) \times 10^8 (1.9)^{-1.7} = \$775 \times 10^6 . $$
For copper, the threat point rent is
\[ R_{\text{NC}}^* = 0, \quad R_{\text{NP}}^* = (1.5 - 1.1) 97.2 \times 10^8 (1.5)^{-1.48} = 930.1 \times 10^6. \]

**The Solutions to the Static Model**

The model is first applied to cobalt, considering ferromanganese deposits a single product resource where only cobalt is of interest, then to cobalt and nickel as joint products, and finally to cobalt, nickel and copper as joint products. The purpose of this is to trace the sensitivity of the solutions to single product and joint product formulations. In particular, it is desirable to investigate how the actors in the cobalt, nickel and copper markets make trade-offs when they are compelled to bargain jointly.

Further, several different variations of Scenario 1 will be tested to determine whether there is a preferred model that best captures the essential elements of the problem. In all, nine variations of Scenario 1 are considered and the results summarized in Table 4.1.

Next, Scenarios 2 and 3 are analyzed using the complete joint product formulations.

There are two basic techniques available for solving the model. The first method involves taking partial derivatives of the objective function with respect to the policy variables, equating to zero (these being the boundary conditions) and thereby securing a set of simultaneous equations which can be solved to yield the optimal values of the policy variables. This, however, can rapidly become very cumbersome if the equation is somewhat complicated and the number of terms even moderately large.

The other technique involves undertaking a global search of all values of the objective function, with specified bounds, for possible combinations
of policy variables. Provided the number of policy variables is not large, the cycle time on a computer is quite small and the global search method is more straightforward than the simultaneous equations method. Both methods were used to solve the following models, depending on the complexity and computational time involved.

Scenario 1: Both NP and NC produce, no transfer payments

A: Same Market-Share for Each Mineral

The model is solved for cobalt, nickel and copper with the same market share variable for all three. The purpose of this is to investigate the impact of adding nickel and copper NP and NC to the cobalt analysis. The relative size of the nickel and copper markets is much larger than the cobalt market and it may be of some interest to determine the consequences of linking the markets in a general commodity agreement that covers all three minerals.

(i) Cobalt

\[ R_{NP} = (P - 4.3) \text{BAP}^{-1.7} \]
\[ R_{NP}^* = 39.2 \times 10^6 \]
\[ R_{NC} = (P - 5.1) (1 - B) \text{AP}^{-1.7} \]
\[ R_{NC}^* = 0 \]
\[ A = 7.82 \times 10^8 \]

The symbols have the meanings assigned to them in Chapter 2.

\[ \max R = (R_{NP} - R_{NP}^*) (R_{NC} - R_{NC}^*) \]

The game solution resulted in

\[ P = 11.04/\text{Kg}, B = 0.721. \]

The NP have a market share of 0.721 and the world price is decided at $11.04/\text{Kg}.$
\[ R_{NP} = \$64.08 \times 10^6, \quad R_{NC} = \$21.86 \times 10^6. \]

The price of $11.04/Kg is higher than the real price of $8.8/Kg that prevailed in 1975. It seems that in 1975, full market power was not being exerted by the producers of cobalt so that the price was somewhat lower than the monopoly price. However, it may be expected that as Zaire and others see the threat of new entry posed by ocean mining and reconcile themselves to its inevitability, they will raise the price of cobalt to its monopoly level to maximize short term gains. There is little point in keeping the price below the monopoly level if new entry cannot be discouraged. Since ocean mining cannot be discouraged in the long run, Zaire and others may as well maximize short run rent. It is instructive to note that by January 1978, the real price of cobalt (expressed in 1975 dollars) had indeed been raised to $12.1/Kg.

The game solution does not yield a monopoly price because of the different marginal costs of the NP and the NC. It does, however, solve for the price where the rents of both are maximized, subject to bargaining.

The net demand for cobalt metal, in this scenario, is $13.2 \times 10^6$ Kg. This implies that the NP produce $3.68 \times 10^6$ Kg from the deep oceans. Since these numbers are based on 1975 data, they understate potential production from offshore mines because by the time ocean mining gets underway, autonomous growth in demand will have raised the total world demand levels by about a third. Commercial ocean mining is not expected to start until 1985 at the earliest, and more likely by 1990. Since total demand will be greater, the absolute share of ocean mining and consequently the rents of production, will also be higher than indicated by the bargaining model which solves for an outcome that simulates both onshore and offshore mining in 1975. In any event, the relationship among the various rents and production levels will not change, just their magnitude.
The technological development that makes deep ocean mining possible has changed the environment for the world cobalt industry which must adjust to potentially large new sources of supply. In this situation the NP will pursue a policy of minimizing the costs inflicted on them by the entry of NC in the market, who of course will pursue a policy of maximizing their rents of production. The bargaining model developed here solves for the pareto-optimal outcome, given the strategies of the NP and the NC.

Since the first generation of ocean mining firms is expected to consist of five consortia and each consortium will probably operate one mine, the cobalt mining operation will have to function at well below capacity to conform to the bargaining solution. Each mine site has an annual capacity of $6 \times 10^6$ Kg so that at full capacity the five consortia could easily satisfy the world net demand for cobalt. The total market share of the mining consortia is $3.68 \times 10^6$ Kg under the solution obtained above, which implies a 12% capacity utilization per mine in 1975 and 16% by 1985. While this does not mean that only 12% or 16% of the nodules will be mined since the total mining operation must take into account the demand for nickel and copper as well, as shown in subsequent analysis, it does imply that with improved technology, a decrease in mining costs or any other change in a bargaining parameter, the ocean mining consortia will be able to expand output rapidly. This will be especially true if the unprocessed or semi-processed ore is stockpiled near the refining sites. This excess capacity could be a source of vexation and temptation to the mining consortia and over time it may be that the land-based producers will feel increasing pressure on their market share. Once the inevitability of ocean mining is established, the economic dimension of the bargaining game may continue to shift in favor of the consortia from the present NC.
The ratio of ocean-based cobalt reserves to land-based cobalt reserves is high enough for the former to be uninfluenced by issues of depletion and the latter influenced by concerns over exhaustion. This implies that while marginal costs will remain constant in real terms over the near future for ocean mining, they can be expected to rise hyperbolically for land-based mining. The convergence in marginal costs will further erode the bargaining position of the NP.

The strategy for the NP, in the short run, must take the arguments just presented into account. Since preventing entry by the NC results in a threat point outcome for the NP, it is better to negotiate because a bargained solution dominates the threat. However, once the NP are reconciled to new entry there is no reason why until entry takes place prices should not be set to maximize profits. There is no longer a restraint on exercising full market power. This indeed is what seems to be happening in the world cobalt market. From $8.8 Kg in 1975 the real price has gone to $12.1 Kg in early 1978 with a still higher price anticipated by the end of the year. Since the price elasticity of demand in the short run is around -0.3 in the relevant price range, a steady rise in real prices may be expected until ocean mining starts. After the onset of offshore production, the price will then fall to around $11/Kg which is the intermediate term equilibrium bargained price. This price will, of course, change as the relative marginal costs change with technological evolution and operating experience offshore and declining grade quality of the ores onshore.

(ii) **Cobalt and Nickel**

The objective functions of the NP and NC are expanded to include the rents for nickel. The NP and NC bargain simultaneously about the market
share and the prices of cobalt and nickel. In this scenario, the NC consider cobalt and nickel as a joint product, and the NP unite to bargain as a unit.

The formulation of the model is based on the joint product model discussed in Chapter 2. The subscripts 1 and 2 refer to cobalt and nickel, respectively.

\[
R_{NP} = (P_1 - 4.3)BA_1P_1^{-1.7} + (P_2 - 1.6)BA_2P_2^{-1.7}
\]

\[
R_{NP}^0 = 814.2 \times 10^6
\]

\[
R_{NC} = (P_1 - 5.1) (1-B)A_1P_1^{-1.7} + (P_2 - 1.9) (1-B)A_2P_2^{-1.7}
\]

\[
R_{NC}^0 = 0
\]

\[
A_1 = 7.82 \times 10^8
\]

\[
A_2 = 76.96 \times 10^8
\]

\[
\text{Max } R = (R_{NP} - R_{NP}^0) (R_{NC} - R_{NC}^0)
\]

The bargaining solution is

\[
P_1 = \$11/\text{Kg}, \quad P_2 = \$4.1/\text{Kg}, \quad B = 0.72
\]

\[
R_{NP} = 1322.4 \times 10^6, \quad R_{NC} = 452.6 \times 10^6
\]

The price for cobalt at $11/Kg and the market share for the NP at 0.72 is very similar to the values of $11.04/Kg and the market share of 0.721 obtained in the preceding analysis. The rents to the NP for cobalt are $64 \times 10^6$, which are almost identical to the rents of $64.08 \times 10^6$ obtained in the case preceding. As long as nickel and cobalt are tied to the same market share, the actors in the cobalt market turn out to be indifferent between bargaining separately and bargaining jointly with the
actors in the nickel market. This happens to be the outcome of this particular game and is not a general result of linking objective functions.

It turns out later, in another scenario, that the nickel market provides an umbrella for the cobalt market and the game outcome in this scenario is actually dominated by the actors in the nickel market. This works to the disadvantage of the NP for cobalt, as will be shown subsequently.

The bargained price for nickel at $4.1/Kg is somewhat lower than the price that prevailed in 1975, $4.5/Kg. The rents to the NP for nickel are $1258.4 \times 10^6$ which indicates that the size of the nickel market is far larger than the cobalt market, and consequently the NP and NC for nickel may dominate the bargaining. The rents of $1258.4 \times 10^6$ are lower than the rents of $1732.5 \times 10^6$ secured by them before the advent of ocean mining, but considerably higher than the threat point rents of $775 \times 10^6$. It clearly pays the NP to bargain.

The solution for nickel also indicates that perhaps in 1975 nickel was being overpriced. This could be because in 1975, and until very recently, the price-setter in world nickel markets was INCO of Canada and the price of $4.5/Kg may have been the profit maximizing price for INCO but not for the industry as a whole. With the erosion of INCO's pre-eminence in the world nickel market the price of the metal declined in real terms from 1975 to 1977. In January 1978, the price of the metal was $4.15/Kg in constant 1975 dollars. This compares with the bargained price of $4.1/Kg.

An interesting feature of the nickel market is that the most important onshore producer, INCO, is also the dominant member of an ocean mining consortium. A well-behaved monopolist would attempt to secure control of alternative sources of supply in order to minimize competitive threat. INCO seems to be responding to this theory. As a member of an ocean mining con-
sortium it belongs to both the NP and the NC and is in an enviable position to influence both sides in the bargaining process. Its strategy is probably to maximize total rents, that is, from both onshore and offshore mining, rather than concentrate on just land-based production. It probably expects to make up from ocean mining any rents it may have to forego from onshore mining as a consequence of a bargain between the NP and NC.

(iii) Cobalt, Nickel and Copper

The objective functions of the NP and NC are further expanded to incorporate the actors in the copper market. Once again, the NP and NC bargain for the same market share across minerals. The subscript 3 refers to copper.

\[
\begin{align*}
R_{NP} &= (P_1 - 4.3)BA_1P_1^{-1.7} + (P_2 - 1.6)BA_2P_2^{-1.7} + (P_3 - 1.1)(1-B)A_3P_3^{-1.48} \\
R_{NP}^o &= 1744.3 \times 10^6 \\
R_{NC} &= (P_1 - 5.1)(1-B)A_1P_1^{-1.7} + (P_2 - 1.9)(1-B)A_2P_2^{-1.7} + (P_3 - 1.5)(1-B)A_3P_3^{-1.48} \\
R_{NC}^o &= 0 \\
A_1 &= 7.82 \times 10^8 \\
A_2 &= 76.96 \times 10^8 \\
A_3 &= 97.20 \times 10^8 \\
\text{Max } R &= (R_{NP} - R_{NP}^o)(R_{NC} - R_{NC}^o) \\
P_1, P_2, P_3 &= \text{price of } 11.2/\text{Kg, } 4.2/\text{Kg, } 3.9/\text{Kg, } B = 0.66 \\
R_{NP} &= 3606.7 \times 10^6, R_{NC} = 1609.7 \times 10^6
\end{align*}
\]

The bargaining outcome is

\[
\begin{align*}
P_1 &= 11.2/\text{Kg}, P_2 = 4.2/\text{Kg, } P_3 = 3.9/\text{Kg, } B = 0.66 \\
R_{NP} &= 3606.7 \times 10^6, R_{NC} = 1609.7 \times 10^6
\end{align*}
\]

The price of $11.2/\text{Kg} for cobalt is again close to the prices obtained in the two earlier cases. The joint market share of 0.66 for the NP, however,
is lower than the 0.72 that prevailed earlier. The solution implies rents of \(58.6 \times 10^6\) for the NP for cobalt which are lower than the rents of about \(64 \times 10^6\) in the two cases preceding. The NP for nickel obtain rents of \(1151.5 \times 10^6\) which are lower than the \(1258.4 \times 10^6\) in the earlier case. The rents to the NP for copper are \(2396.6 \times 10^6\) which compare favorably with the threat point rents of \(930.1 \times 10^6\) for them. Clearly, the size of the copper market dominates the cobalt and nickel markets. Both the NP for cobalt and nickel are forced to forego rents when they bargain jointly with the NP for copper.

The price for nickel at \$4.2/Kg\) is slightly higher than the \$4.1/Kg\) in the earlier analysis, but the market share at 0.66 is lower than the share of 0.72 when only nickel and cobalt were considered.

The negotiated price of copper at \$3.9/Kg\) is slightly higher than the price of \$1.23/Kg\) which prevailed in 1975. The latter price was admittedly depressed by historical standards but the negotiated price is considerably larger than even the historical peaks in the price of copper. There is an important difference in the world markets for nickel and cobalt on one hand and copper on the other. In the case of copper, there is no dominant producer and no recognized price-setter. Despite the efforts of CIPEC, the copper cartel prices are much closer to their competitive levels at present than in the markets for either cobalt or nickel. The bargained price represents an approximation of the rent maximizing price that would be set by an oligopolistic or monopolistic industry.

**B: Separate Market Shares for Each Mineral**

The basic price and market share model was simulated with the modification that separate market shares were determined for each mineral. This provided greater flexibility in the bargaining.
(iv) Cobalt and Nickel

The objective functions of the NP and NC for cobalt and nickel are added together and a bargained outcome of prices and market shares sought.

\[
R_{NP} = (P_1 - 4.3)B_1A_1P_1^{1.7} + (P_2 - 1.6)B_2A_2P_2^{1.7}
\]

\[
R_{NP}^* = 814.2 \times 10^6
\]

\[
R_{NC} = (P_1 - 5.1)(1-B_1)A_1P_1^{1.7} + (P_2 - 1.9)(1-B_2)A_2P_2^{1.7}
\]

\[
R_{NC}^* = 0
\]

The subscripts 1 and 2 refer to cobalt and nickel, respectively.

\[
\text{Max } R = \left( R_{NP} - R_{NP}^* \right) \cdot \left( R_{NC} - R_{NC}^* \right)
\]

The bargaining outcome is

\[
P_1 = $10.5/Kg, \quad P_2 = $4.1/Kg, \quad B_1 = 0.98, \quad B_2 = 0.71
\]

\[
R_{NP} = $1328.14 \times 10^6, \quad R_{NC} = $447.57 \times 10^6
\]

The price of cobalt at $10.5/Kg is lower than encountered in the previous cases, but the market share of the NP at 0.98 is much higher. The rents to the NP for cobalt are $87.3 \times 10^6 and these are considerably higher than the rents earned in the cases analyzed thus far. Clearly, by introducing flexibility in the market shares, the NP for cobalt gain. It pays them to have the cobalt and nickel markets linked in the bargaining process. The far larger size of the nickel market shifts the focus of bargaining to that metal and the NP for cobalt scarcely lose market share. They do, however, settle for a price lower than that secured in the fixed market share, joint product or single product negotiations but since their objective is maximizing rents rather than price, this can be no hardship.
The prices of $4.1/Kg for nickel is the same as attained for the fixed share cobalt and nickel case and the market share of 0.71 for the NP for nickel is only slightly lower than the 0.72 attained in the earlier bargain. Owing to the slight decrease in market share, the rents for the NP for nickel fall to $1240.8 x 10^6 from $1258.4 x 10^6. The loss of $17.6 x 10^6 for the NP for nickel is less than the gain of $23.3 x 10^6 for the NP for cobalt, so that as a bargaining group the NP are better off than in the fixed market share case. To persuade the NP for nickel to adopt the flexible market share position, the NP for cobalt could make a side payment of $17.6 x 10^6 and still emerge $5.7 x 10^6 to the good.

The NC earn total rents of $447.6 x 10^6 which are lower than the total rents of $452.6 x 10^6 obtainable in the fixed market share case. The difference of $5 x 10^6 is very close to the net gain of $5.7 x 10^6 for the NP. The NP for cobalt might then have to make a side payment of $5 x 10^6 to the NC to persuade them to agree to this game. They would still be $0.7 x 10^6 ahead. The implication is that once side payments are made the fixed and flexible market share games are almost equivalent. Without side payments, of course, the NP for cobalt gain with the flexible market shares and the NP for nickel and the NC lose. The fixed market share analysis shows the consequences of linking two very unequal markets in a joint commodity agreement. The outcome on the allocation of production is dominated by the actors in the much larger market. The market share for the NP for nickel is forced on the NP for cobalt in the fixed share case. When the markets are delinked, the outcome for the nickel market is hardly changed, but the rents to the NP for cobalt rise by 36% and the price falls by 4.5%

Since the ferromanganese deposits are a joint product resource, the ocean mining firms would clearly like to extract both nickel and cobalt
owing to the common costs of exploration side preparation and transportation. It is their joint product attribute that permits the allocation of long run marginal costs and thereby lowers per mineral costs since exploration, harvesting and transportation are shared costs. If only one mineral was extracted, all costs would have to be allocated to it and this would make ocean mining uncompetitive. The fixed market share model implies a demand for offshore cobalt of about $5 \times 10^6$ Kg and for offshore nickel of about $260 \times 10^6$ Kg by 1985. With five consortia, the per firm output would have to be $1 \times 10^6$ Kg of cobalt and $52 \times 10^6$ Kg of nickel. Since each oceanbed mine can yield a flow of $6 \times 10^6$ Kg of cobalt and $39 \times 10^6$ of nickel, the solution implies a 17% capacity utilization per site for cobalt and 133.3% for nickel. This means that two mine sites per consortium will be needed with each site having an 8% utilization for cobalt and a 67% utilization for nickel. Since enough ferromanganese deposits must be mined to extract $52 \times 10^6$ Kg of nickel, each consortium must harvest $4 \times 10^6$ metric tons of dry nodules per annum by 1985.

The flexible market share model indicates a demand of $0.38 \times 10^6$ Kg for oceanbed cobalt and $269.6 \times 10^6$ Kg for oceanbed nickel by 1985. This means that ocean mining will really be undertaken only for nickel and all costs will have to be allocated to nickel, which would defeat the purpose of exploiting a joint product resource.

This indicates the difficulty in linking markets of greatly unequal sizes. The smaller cobalt market is dominated by the nickel market and the game solution concentrates on allocating the rents from nickel production because the rents from cobalt production are a small fraction of the former.
(v) Cobalt, Nickel and Copper

As before, the objective functions are expanded to incorporate the actors in the copper market. The results are instructive and illustrate, again, the significant impact of linking the copper market with those of cobalt and nickel in a commodity bundle agreement. The subscripts 1, 2 and 3 refer to cobalt, nickel and copper, respectively.

\[ R_{NP} = (P_1 - 4.3)B_1A_1P_1^{-1.7} + (P_2 - 1.6)B_2A_2P_2^{-1.7} + (P_3 - 1.1)B_3A_3P_3^{-1.48} \]

\[ R_{NP}^0 = 1744.3 \times 10^6 \]

\[ R_{NC} = (P_1 - 5.1)(1-B_1)A_1P_1^{-1.7} + (P_2 - 1.9)(1-B_2)A_2P_2^{-1.7} + (P_3 - 1.5)(1-B_3)A_3P_3^{-1.48} \]

\[ R_{NC}^0 = 0 \]

\[ \text{Max } R = (R_{NP} - R_{NP}^0) (R_{NC} - R_{NC}^0) \]

The negotiated outcome is

\[ P_1 = $12.4/Kg, P_2 = $4.6/Kg, P_3 = $3.4/Kg \]

\[ B_1 = 0, B_2 = 0, B_3 = 1 \]

\[ R_{NP} = $3654.31 \times 10^6, R_{NC} = $1631.19 \times 10^6 \]

The solution allocates all cobalt and nickel production to offshore mining at prices higher than obtained in the previous cases. This would have each mining consortia producing about 2.9 \times 10^6 Kg of cobalt and 152.9 \times 10^6 Kg of nickel from offshore mines by 1985. The ratio of nickel to cobalt abundance in ferromanganese deposits is around 6.5 to 1 and the ratio of nickel to cobalt net demand is 52.7 to 1. While only one mine (at less than 50% capacity utilization) would meet the production needs
of each consortia, four mines would be needed to satisfy the nickel requirements of each consortium.

To meet all the world net demand for nickel from offshore mining by 1985 would require the harvesting of $58.8 \times 10^6$ tons of dry nodules. This does not seem feasible by 1985, when given the technological and investment constraints, not more than ten offshore mines could be in operation.

The bargaining solution also allocates no copper production to ocean-bed mining. The price again is much higher than historically recorded and would probably not be politically acceptable to consumers of copper. The very large size of the copper market in relation to nickel and cobalt markets accounts for this solution. The NP for copper dominate the NP for nickel and cobalt when the markets are linked in a negotiating process and bargain away all nickel and cobalt production in exchange for maintaining their entire market share. The NP for nickel and cobalt end up with no rents at all. The NP for copper obtain rents of $3654.3 \times 10^6$ in 1975 or $4860.2 \times 10^6$ by 1985. The NC secure rents of $1631.2 \times 10^6$ in 1975 or $2169.5 \times 10^6$ by 1985. As far as the NC are concerned, the rents for the fixed and flexible market share cases are comparable. The NP for copper gain considerably by moving from fixed shares (with rents of $2396.5 \times 10^6$ in 1975) to flexible shares (with rents of $3656.3$ in 1975). The NP for nickel lose rents of $1151.5 \times 10^6$ and the NP for cobalt lose rents of $58.6 \times 10^6$ in moving from the fixed to flexible market share models. The NP for copper would have had to make total side payments of $1210.1 \times 10^6$ to the NP for nickel and cobalt in 1975, leaving them with rents of $2453.2 \times 10^6$, which is still better off than the fixed market share case.
(vi) Scenario lb: The Introduction of Consumer Surplus

The introduction of consumer surplus to the objective function of the NC drastically changes the results. The threat point for the NC is no longer zero, but rather, the consumer surplus at the limit or no-entry price.

The rent function of the NC is also expanded to include the consumer surplus at the negotiated price. In none of the cases analyzed was a negotiated solution obtained. The threat point always dominated. When consumer surplus is taken into account, negotiations break down and the non-negotiated solution is preferred. The reason for this is illustrated by the 3 product case (cobalt, nickel and copper) with flexible market shares. The objective function of the NP remains unchanged and is given by

\[ R_{NP} = (P_1 - 4.3)B_1A_1P_1^{-1.7} + (P_2 - 1.6)B_2A_2P_2^{-1.7} + (P_3 - 1.1)B_3A_3P_3^{-1.48} \]

The threat point for the NP is also unaltered

\[ R_{NP}^o = 1744.3 \times 10^6. \]

The objective function for the NC, however, now includes the consumer surplus at \( P_1, P_2, P_3 \), the negotiated prices for cobalt, nickel and copper. Accordingly,

\[ R_{NC} = (P_1 - 5.1)(1-B_1)A_1P_1^{-1.7} + \int_{P_1}^{20} A_1P_1^{-1.7} \, dP_1 \]

\[ + (P_2 - 1.9)(1-B_2)A_2P_2^{-1.7} + \int_{P_2}^{15} A_2P_2^{-1.7} \, dP_2 \]

(equation continued on following page)
The threat point for the NC now becomes

$$R_{NC}^o = \left\{ \frac{20}{5.1} A_1 P_1^{1.7} dP_1 + \frac{15}{1.9} A_2 P_2^{1.7} dP_2 + \frac{8}{1.23} A_3 P_3^{1.48} dP_3 \right\}.$$

For copper, the lower limit of integration is the 1975 world price rather than the marginal cost of production for the NC because the latter at $1.5/Kg was higher than the world price. For cobalt and nickel the lower limit of integration is the limit price, which is the marginal cost of production for the NC.

Solving for $R_{NC}^o$ leads to

$$R_{NC}^o = \frac{A_1}{0.7} \left[ \frac{1}{(5.1)} 0.7 - \frac{1}{(20)} 0.7 \right] + \frac{A_2}{0.7} \left[ \frac{1}{(1.9)} 0.7 - \frac{1}{(15)} 0.7 \right]$$

$$+ \frac{A_3}{0.48} \left[ \frac{1}{(1.23)} 0.48 - \frac{1}{(8)} 0.48 \right].$$

where

$$A_1 = 7.28 \times 10^8, A_2 = 76.96 \times 10^8, A_3 = 97.2 \times 10^8$$

or

$$R_{NC}^o = 16,439.4 \times 10^6.$$

Given this threat point for the NC, clearly no negotiated solution is possible. The maximum rents earned by producer units from the NC are less than $1.7 billion after a cooperative outcome. These are a small fraction of the consumer surplus of more than $16 billion that results from non-cooperation. The consumer surplus at the negotiated point when
the rents to the NC are $1.7 billion is around $12.17 billion. The total
gain to the NC after negotiation is close to $13.9 billion which is more
than $2 billion under the gain to the NC from non-cooperation. Moreover,
the gain in consumer surplus for the NC far exceeds the loss in rent for
the NP as a consequence of negotiation breaking down. This result is
hardly surprising when it is considered that consumers gain by extracting
the lowest possible price from the market.

In discussing a regime for the minerals of the deep ocean, the barg-
gaining seems to be between the NP and the potential producer groups from
the NC. As far as the purely economic interests of consumers from the NC
are concerned, no regime may be the best solution. The efforts to devise
a regime seem to be an attempt to cater to producers groups from both the
NP and NC. When political considerations are ignored, the regime structure
may really be one that is a facade for a two-part cartel that effectively
fosters a collusive relationship between ocean mining consortia and the NP.
There are, of course, political reasons why a seabed regime is desirable,
but the trade-off between the political utility of such an agreement and
its economic disutility to the consumers of the NC should be clearly kept
in mind when price maintenance schemes and deep ocean mining production
ceilings are formulated.

To the extent the utility or benefits from navigation rights, the
freedom of scientific research, access to secure sources of supply, ac-
knowledging the moral obligation of international egalitarianism and the
gains from international interdependence can be quantified, it would be
useful to compare them with the loss in consumer surplus. The NC are
largely the industrialized democracies and the NP, with the notable and
complicating exception of Canada, are the nations of the South. The non-
economic benefits of a law of the sea agreement as far as the NC are concerned should be roughly equal to the loss in consumer surplus less gain in rents of production for a negotiated settlement to be worthwhile. In other words, the quantifiable non-economic, that is, largely political, benefits of a law of the sea agreement accruing to the industrialized nations of the North should be in the region of $2 billion per year and increasing over time. The lack of an agreement on ocean mining will have a negative impact on the ocean mining consortia, but may not be against the best interests of the NC as a whole. The $2 billion figure may be overstating matters somewhat since the analysis has neglected the multiplier effects of ocean mining on the economies of the NC. Perhaps the political utility of an agreement together with the psychic income to be derived from increased national security is worth the economic disutility, but unless a careful assessment is made it is difficult to judge.

Even if the non-economic benefits to the NC are not equivalent to $2 billion or more per year, it may still be desirable to reach a negotiated solution.

The pressure of international egalitarianism and interdependence, coupled with the moral imperatives of U.S. foreign policy, might argue for a transfer of real resources to the NP who are, largely, the nations of the South. A negotiated solution would have the irresistible charm of satisfying the liberal elites in the U.S. and Western Europe as well as effectively hiding the $2 billion plus a year subsidy from the NC to the NP from the scrutiny of the more conservative constituencies within the nations of the North. There seems to be growing resistance among pragmatic commentators in the U.S. to the idea of large resource transfers from the North to South as called for in the New Economic Order. Perhaps
the implicit transfer implied in a negotiated solution may be a less objectional form of undertaking aid to the South. Further, the negotiated solution, despite its implication for reduced consumer surplus, would be consistent with the general philosophy of commodity agreements as espoused by the United Nations Conference on Trade and Development (UNCTAD) (on behalf of the South) and the Orderly Marketing Arrangements, lately so dear to negotiators from the North. Both commodity agreements and Orderly Marketing Arrangements (OMA) imply a loss of consumer surplus through higher prices or protected markets, which translates into higher prices. The revealed preference is then, for some sacrifice of consumer surplus in favor of a gain to producer units from the North and the South and for the gain in political utility derived from reduced international tensions, greater stability in world markets, enhanced security of supplies and less uncertain access to sources of supply.

UNCTAD sponsored commodity agreements seem to be acquiring support in the nations of the North and the South. Control over and intervention in mineral markets is no longer the subject of vigorous protest from government officials or corporate planners within the U.S., Western Europe and Japan, and it is fervently advocated by representatives from the nations of the South. A negotiated agreement for the minerals of the deep seabed would be merely a logical and consistent aspect and extension of this phenomenon. Given the long run inevitability of an agreement, the question of interest for producer groups from the NC is how they can maximize potential rents and for producer groups from the NP how they can minimize potential losses or acquire a share of the rents generated by developing the minerals of the deep oceanbed.
C: Other Variations of Scenario 1

Some alternative formulations of the model in Scenario 1 are considered here. The effects of linking copper have been discussed earlier. The impact of partially disengaging the copper market from those of cobalt and nickel is examined by first imposing the fixed market share solution for cobalt and nickel on the copper market and solving for the world price of copper. Next, the copper market is disengaged a bit further by first determining the fixed market share solution for cobalt and nickel and then adding to this solution the objective functions of the NP and NC for copper. The bargained outcome for the world price of copper and the market shares of the NP and NC for copper is then sought within this two-stage negotiating framework.

The analysis so far has not been particularly realistic in that the process constraint imposed by nature has been neglected. Every manganese nodule contains, among other minerals, cobalt, nickel, and copper in certain proportions. While these proportions have a distribution of values over the entire range of the manganese nodule population, the expected values of the distribution can be used to model relative abundance. Clearly, it is not possible to harvest $x$ units of cobalt from the ocean-bed without also harvesting $y = y(x)$ units of nickel and $z = z(x)$ units of copper. Within limits, the problem is one of fixed proportions of abundance, which, of course, is what one expects from a joint product resource.

It is to address this aspect of ocean mining that the joint product nature of the resource is considered more explicitly in another formulation that follows. A constraint is introduced that acknowledges the relative abundance of cobalt, nickel and copper in ferromanganese deposits. Nickel is about six and a half to seven times more abundant than cobalt and copper
around five and a half to six times. Consequently, an ocean mining operation that produces 1 unit of cobalt also has the potential of producing 7 units of nickel and 6 units of copper. This processing constraint is built into the model by expressing the output shares for nickel and copper as functions of the output share of cobalt. This will obviate the vexing problem of having to exploit the oceanbed mine sites at vastly different rates of capacity utilization suggested by the model solutions when relative abundance constraints are not explicitly considered.

C.1: Partially Disengaged Copper Market

(vii) Copper Price with Predetermined Market Share for Copper

The fixed market share solution of 0.72 for cobalt and nickel (see formulation ii, cobalt and nickel, fixed B) is imposed on the copper market and the world price of copper at this market share is determined. The objective function of the NP for copper is added to the rents accruing to the NP for cobalt and nickel ($1322.4 \times 10^6$) and the objective function of the NC for copper is added to the negotiated rent to the NC for cobalt and nickel ($452.6 \times 10^6$).

\[
R_{NP} = 1322.4 \times 10^6 + (P_3 - 1.1) 0.72 A_3 P_3^{-1.48}
\]

\[
R_{NP}^o = 1744.3 \times 10^6
\]

\[
R_{NC} = 452.6 \times 10^6 + (P_3 - 1.5) 0.28 A_3 P_3^{-1.68}
\]

\[
R_{NC}^o = 0
\]

\[
\text{Max } R = \left( R_{NP} - R_{NP}^o \right) \left( R_{NC} - R_{NC}^o \right)
\]

The negotiated solution is

\[
P_3 = \$3.88/Kg, R_{NP} = 3938 \times 10^6, R_{NC} = 1323.4 \times 10^6
\]
The price of copper is determined to be $3.88/Kg with the NP keeping 72% of the market. The total rents to the NP are $3.94 billion in the separate market shares case and $3.61 billion in the fixed market share case. The price of copper is close to the $3.9/Kg in the fixed market share analysis and higher than the $3.4/Kg in the separate market shares analysis. The rents to the NC at $1.3 billion are lower than the rents of $1.61 billion in the fixed share and $1.63 billion in the separate shares cases. The approximate gain of $0.3 billion to the NP is matched by the approximate loss of $0.3 billion to the NC. Within the narrow context of the game a transfer payment of $0.3 billion from the NP to the NC would make the outcomes in the various cases equivalent. For the individual markets, of course, the outcomes are far from equivalent.

The 0.28 market share solution implies that in 1975, 3.71 x 10^6 Kg of cobalt, 195.7 x 10^6 Kg of nickel and 365.9 x 10^6 Kg of copper would have to be recovered from the manganese nodules. If it is assumed that cobalt demand rises by 3% per annum from 1975 to 1985, nickel and copper demand by 2%, then almost 5 x 10^6 Kg of cobalt, 240 x 10^6 Kg of nickel, and 450 x 10^6 Kg of copper will be harvested from the oceanbed by 1985, when actual mining is expected to start. The solution implies that 3 mine sites per consortium would have to be developed to satisfy the copper demand. This is not feasible in terms of the investments that must be made, nor is it likely mine sites will be opened just to satisfy copper demand, since the implied nickel demand can be met by 2 sites per consortium and the cobalt demand by 1 site each.

Further, the high price of copper is also not likely to be acceptable to consuming countries since it is far above historical peaks. The copper market is simply too large to be linked with the cobalt and
nickel markets unless a process constraint is introduced.

C.2: Process Constraints with Linked Market Shares

The process constraint is introduced explicitly in this scenario by linking the nickel and copper production from offshore mines to that of cobalt. Since nickel is almost 7 times as abundant as cobalt, and copper almost 6 times as much, the process constraint is designed so that for every unit of cobalt produced, a maximum of 7 units of nickel and 6 units of copper are extracted.

Hence for nickel:

\[(1-B_2) A_2 p_2^{-1.7} = 7(1-B_1) A_1 p_1^{-1.7}\]

or \[B_2 = 1 - 0.662 \frac{p_1^{-1.7}(1-B_1)}{p_2^{-1.7}}\]

And, for copper

\[B_3 = 1 - 0.449 \frac{p_1^{-1.7}(1-B_1)}{p_3^{-1.7}}\]

(viii) Cobalt and Nickel

The objective functions of the NP and NC for cobalt and nickel are combined and a negotiated solution for prices and market share is sought with the process constraint kept in mind during the negotiations. The solution can then be compared with other cases where the nickel market was linked with the cobalt market.
\[ R_{NP} = (P_1 - 4.3)B_1 A_1 P_1^{-1.7} + (P_2 - 1.6)(A_2 P_2^{-1.7} - 7A_1 P_1^{-1.7}(1-B_1)) \]

\[ R_{NP}^* = 814.2 \times 10^6 \]

\[ R_{NC} = A_1 P_1^{-1.7} (1-B_1) \left( (P_1 - 5.1) + 7(P_2 - 1.9) \right) \]

\[ R_{NC}^* = 0 \]

\[
\text{Max } R = \frac{(R_{NP} - R_{NP}^*)(R_{NC} - R_{NC}^*)}{P_1, P_2, B_1}
\]

The negotiated solution is:

\[ P_1 = 8.2/\text{Kg}, \ P_2 = 4.2/\text{Kg}, \ B_1 = 0, \ B_2 = 0.77 \]

\[ R_{NP} = 1346.8 \times 10^6, \ R_{NC} = 419.8 \times 10^6. \]

The world price of cobalt is set at $8.2/Kg, of nickel at $4.2/Kg. The NP for cobalt lose their entire net demand market to offshore production and the NP for nickel retain 77% of the net demand market. At these prices offshore production is determined to be $21.86 \times 10^6$ Kg for cobalt in 1975 or $29 \times 10^6$ Kg by 1985 and $154.3 \times 10^6$ Kg for nickel in 1975. Each consortium would operate one mine at 70% of capacity in 1975 and close to capacity by 1985. The value of $B_1$ and $B_2$ will change over the years because the net demand markets for cobalt and nickel are expected to grow at different rates. This will change the ratio of $A_2$ to $A_1$ over time, which in turn will influence the value of $B_2$. The difference, however, will not be large if as expected the net demand growth for cobalt is 3% and for nickel 2%.

The negotiated prices for both cobalt and nickel are lower than in
1975, with cobalt at $8.2/Kg versus the $8.8/Kg that prevailed in 1975 and with nickel at $4.2/Kg versus the $4.47/Kg in 1975. The NP for cobalt lose completely in this bargain. Their market share of net demand is zero compared with 0.72 when negotiating separately, with 0.72 when nickel and cobalt markets are locked in a one share negotiation, with 0.66 when cobalt, nickel and copper markets are linked rigidly and with 0.98 when nickel and cobalt produces are linked with flexible market shares. It does compare with the case, however, when cobalt, nickel and copper markets are linked with flexible shares. The NP for nickel retain 0.77 of the net demand which is better than the 0.72 with cobalt linked in a fixed share and 0.71 with cobalt linked in a flexible share negotiation. It is also better than being linked with cobalt and copper in the fixed share case, (0.66) and decidedly superior to being linked with copper and cobalt in the flexible share case (0).

The consumers of cobalt in the NC gain consumer surplus through lower prices and the mining consortia from the NC capture all the rents of production. The consumers of nickel from the NC also gain through lowered prices for that metal. The total rents to the NC at $419.8 x 10^6 are slightly lower than the rents of $452.6 x 10^6 and $447.6 x 10^6 in the fixed and flexible share cases. The NP for nickel appropriate rents of $1.35 billion, which is better than the almost $1.26 billion and $1.24 billion in the fixed and flexible share cases. The NP for nickel, therefore, could make a side payment of $90 million to the NP for cobalt (which is more than the amount of rent $87 million, forgone by them in any of the cases) and be indifferent to the various outcomes. Except for Morocco, the other NP for cobalt extract it as a by-product of copper, lead, zinc or nickel. If the NP for the metal were compensated at around $80 -
$90 million per annum with the payments rising over time for a few years (a form of protection money) then they might be persuaded to phase out their cobalt operations. Morocco, the only producer of primary cobalt, will have depleted its economic reserves by 1985 anyway, so its bargaining power will wane over time. In the short run, of course, it will not be politically feasible to shut down operations so the game solution is not acceptable for 1975. However, by 1985 the solution may be more acceptable. Morocco will have become, at best, a very minor producer and the other nations could begin shifting out of cobalt. In the meanwhile, the NP for cobalt would raise real prices and secure as much monopoly rent as possible. This is indeed what appears to be happening. By early 1978, the real price of cobalt was almost 40% higher than its 1975 value, and rising. The short term monopoly profits plus a stream of transfer payments for say, ten years, might be sufficient to persuade the NP for cobalt to agree to a negotiation outcome where the entire net world demand is met by offshore cobalt by perhaps 1990. The political feasibility of the transfer payment is open to debate. It might be noted, however, that both Zambia and Zaire, which are major producers of cobalt, are also important producers of copper, so that if some agreement was reached on the latter mineral, they might eventually be willing to forego the production of cobalt.

The other producers of cobalt, besides Morocco, are Botswana, New Caledonia, Canada, and Australia, all of whom produce cobalt as a by-product of copper or nickel. With an agreement on nickel and copper, there would be no need for any considerable explicit side payments to these countries. The side payments could be incorporated implicitly, in the prices for nickel and copper. The only problem, then, would be
Morocco, which for a few years might demand explicit compensations of a few million dollars a year, but with its cobalt reserves being depleted, it can hardly plead hardship beyond 1990. In summary, explicit transfer payments to Morocco and implicit transfer payments to the other NP for cobalt (in the form of prices and market shares for nickel and copper) should provide the political mechanism for acceptance of the negotiated solution.

(ix) Cobalt, Nickel and Copper

The addition of the copper market to the analysis is accomplished, as in the previous case, by suitably expanding the objective functions of the NP and NC.

\[ R_{NP} = (P_1 - 4.3)B_1A_1P_1^{-1.7} + (P_2 - 1.6)B_2A_2P_2^{-1.7} + (P_3 - 1.1)B_3A_3P_3^{-1.48} \]

where

\[ B_2 = 1 - 7A_1 \left( \frac{P_1}{A_2} \right)^{-1.7} \left( 1 - B_1 \right) \]

and

\[ B_3 = 1 - 6A_1 \left( \frac{P_1}{A_2} \right)^{-1.7} \left( 1 - B_1 \right) \]

Substituting \( B_2 \) and \( B_3 \) in \( R_{NP} \) leads to

\[ R_{NP} = (P_1 - 4.3)B_1A_1P_1^{-1.7} + (P_2 - 1.6)(A_2P_2^{-1.7} - 7A_1P_1^{-1.7} (1 - B_1) ) \]

\[ + (P_3 - 1.1) (A_3P_3^{-1.48} - 6A_1P_1^{-1.48} (1 - B_1) ) \]

\[ R_{NP}^0 = \$1744.3 \times 10^6 \]

\[ R_{NC} = (P_1 - 5.1)(1 - B_1)A_1P_1^{-1.7} + (P_2 - 1.9)(1 - B_2)A_2P_2^{-1.7} + (P_3 - 1.5)(1 - B_3)A_3P_3^{-1.48} \]
or, after simplifying,
\[
R_{NC} = A_1 P_1^{1.7} (1-B_1) [(P_1-5.1) + 7(P_2-1.9) + 6(P_3-1.6)]
\]
\[
R_{NC}^* = 0
\]
\[
\text{Max } R = (R_{NP} - R_{NP}^*) (R_{NC} - R_{NC}^*)
\]

The negotiated outcome is

\[
P_1 = \$5.4/\text{Kg}, \ P_2 = \$4.9/\text{Kg}, \ P_3 = \$3.7/\text{Kg}
\]
\[
B_1 = 0, \ B_2 = 0.397, \ B_3 = 0.81
\]
\[
R_{NP} = \$3.63 \text{ billion}, \ R_{NC} = \$1.53 \text{ billion}
\]

The market share of the NP for cobalt is again driven to zero, but the world's price also falls from \$8.2/\text{Kg} in the previous case to \$5.4/\text{Kg}. The consumers of cobalt clearly gain and the net demand for cobalt more than doubles.

The market share of the NP for nickel falls to around 0.4 from 0.77 in the previous cases. The price, however, rises from \$4.2/\text{Kg} to \$4.9/\text{Kg}, which is quite high. The rents to the NP for nickel are \$628.7 \times 10^6, which are much lower than the \$1346.8 \times 10^6 earned in the previous case. The impact of linking the copper market is to raise nickel prices, depress the market share of the NP and lower cobalt prices.

The copper price at \$3.7/\text{Kg} is, again, high, but the NP retain 0.81 of the market share and earn rents of almost \$3 \text{ billion}. The NP for copper would probably have to make a side payment of around \$700 \times 10^6 to the NP for nickel and around \$80 \times 10^6 to the NP for cobalt to secure their cooperation. This would drive the effective prices of copper for
the NP to around $3.1/Kg, which is a figure that is still very attractive to producers and not too offensive to consumers. Since cobalt is often a coproduct of nickel or copper on land, the NP for cobalt may not have to be explicitly compensated by side payments except for short-term flows to countries such as Morocco. The transfer payments to the NP for nickel would cause the effective price to rise to almost $8/Kg (for them), which of course is enough to compensate them for loss of market share, since the concern is over rent -- and not production. The consumers of nickel or copper would probably not be happy with the prices, but the debate really is between producer units from both the NP and NC, and, as an earlier analysis revealed, some consumer surplus may have to be sacrificed to secure an international treaty. The result of a negotiated settlement, it may be noted, would be a very effective joint-cartelization of the world markets for cobalt, nickel, and copper. This may be repugnant to those who still maintain a preference for competitive markets, but it would not be inconsistent with the ideological predilections of UNCTAD, which vigorously tries to foster commodity agreements, nor indeed, with those of international trade negotiators from the industrialized democracies, who, of late, have grown increasingly fond of Orderly Marketing Agreements (OMA). The latter are a subtle form of cartelization. The price subsidies implied in the solution above should also appeal to those liberal elites in the North who believe that the moral imperatives of international egalitarianism and the pressures of international interdependence argue for resource transfers to the South. The mining consortia, too, should have little cause to complain. Each of the five consortia would operate two mines at about 80% of capacity in 1975 and at close to capacity by 1985.
Whether they will be able or willing to make the investments necessary to do so is not apparent. They should be able to do so by 1990.

The model discussed in the pages above seems to be the preferred one for studying rent distribution, prices, and market shares. The negotiated prices of copper and nickel take into account the side payments that must be made to the producers of cobalt by maintaining total rents. Therefore, if the rents on cobalt production fall to zero, and the rents on copper and nickel production rise, then the joint producers of cobalt and nickel and cobalt and copper will not lose rents on balance, which presumably is what they care about. The 7 to 12 year lag time before ocean mining becomes commercially important should provide a sufficient time for adjustments.

Comparison of Alternative Formulations of Scenario 1

The results of the 10 formulations of the model that have been analyzed so far are summarized in Table 4.1 for ease of reference. The greatest variation in prices and market shares is associated with cobalt, whose price ranges from $5.4/Kg to $12.4/Kg, in 1975 dollars. This is probably a range that at the lower end is close to the marginal cost of offshore production, and at the upper end is near the long run monopoly price given the current structure of the market. The main reason for this range appears to be the relatively small size of the net demand market for cobalt, so that when considered by itself, the exertion of market power is manifest and when considered with nickel and copper its rents and market share are bargained away by the NP in an effort to preserve rents in the latter, more significant, markets. Nickel and copper show considerable stability in prices ranging from $4.1/Kg to $4.9/Kg for nickel (compared with $4.5/Kg that prevailed in
1975) and for copper from $3.4/Kg to $3.9/Kg (compared with $2.4/Kg in 1974 and $1.23/Kg in 1975). The price of nickel does not deviate greatly from 1975 levels because presumably the NP were existing close to full market power given that the nickel market for years has been like a monopolist (INCO) with a competitive fringe. Copper prices, on the other hand, rise considerably above 1974-75 levels, indicating that the hitherto ineffective copper cartel (CIPEC), finds cohesion when the NP are given the opportunity to bargain as a unit and consequently market power is exploited.

The fluctuation in market shares is linked with the size of the net demand markets. The market share of the NP for cobalt ranges from 0.98 (only cobalt considered) to 0 (cobalt bargained away by the NP when linked with nickel and copper). The market shares of the NP for nickel and copper fluctuate less because of the much larger sizes of their markets. Nickel, as might be expected, fluctuates more than copper, 0.40 to 0.77, which ranges from 0.63 to 1.00.

In the next two sections scenarios 2 and 3 are discussed.
\[
\begin{array}{cccccccccc}
& b_3 & b_2 & b_1 & b_3 & b_2 & b_1 & p_{NC} & p_{NP} & \\
0.81 & 0.40 & 0.00 & 0.00 & 3.7/9/106 & 4.9/40/106 & 4.1/9/106 & 3.9/106 & 3.9/106 & 3.9/106 \\
& & 0.77 & --- & --- & & & & & \\
1.00 & 1.00 & 1.00 & 3.4/106 & 3.4/106 & 3.4/106 & 3.4/106 & 3.4/106 & 3.4/106 & 3.4/106 \\
& & 0.71 & 0.71 & 0.71 & 0.71 & 0.71 & 0.71 & 0.71 & 0.71 \\
& & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 \\
& & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 & 0.72 \\
\end{array}
\]

**Comparison of Alternative Formulations of Scenario 1**

**TABLE 4.1**
SCENARIO 2: THE NC LICENSE THEIR TECHNOLOGY TO THE NP. ONLY THE NP PRODUCE.

In this scenario it is assumed that the NC, who through their mining consortia are the repositories of the technology required to develop deep seabed minerals, license it to the NP and refrain or are contractually forbidden to produce themselves. The NP use the technology to produce from the ocean floor and pay the NC a royalty per unit of mineral produced.

The NP would probably not produce directly but through a transnational entity such as the "Enterprise" which has been the subject of frequent and protracted debate at the U.N. Law of the Sea Conference. The Enterprise,* which may be the producing arm of a Seabed Authority, would probably purchase the technology from the mining consortia and either produce itself, or arrange for the mining consortia to manage the production under some sort of combined technology licensing and management contract. The rents to the NC would then be those that accrue from the sale of technology and management skills.

The policy variables in this version of the case are the production share of ocean resources, γ, the technology (and management fee) royalty, Q, expressed as a fraction of the world price in dollars per kilogram and paid on that portion of the production which is derived from offshore mining, and the world price P. The technology royalty, Q, is expressed as a function of the P; it is bounded in such a manner that at its upper limit the rents from offshore production are completely appropriated by the NC. This would be the limiting value of Q at which the NP would be interested in producing from the oceanbed.

* It has been so designated for lack of a suitable name. The terms was coined by the delegates to UNCLOS III.
The purpose of the analysis is to model an institutional arrangement rather different from Scenario 1, where both the NP and NC produce, and investigate the changes, if any, in rents to the NP and NC, the share of oceanbed minerals in world demand and the negotiated prices.

The discussion relating to Scenario 1 has made it obvious that process constraints would have to be introduced explicitly in the model. This is done when first nickel and then nickel and copper are linked with cobalt. The impact of linking nickel, cobalt and copper in an international joint commodity agreement continues to be of interest.

(i) Cobalt

The rents to the NP are the sum of rents from land-based production and ocean-based production, less the technology royalty paid to the NC on the latter. The rents to the NC are, of course, the technology royalty on ocean-based production.

\[ R_{NP} = (P_1 - 4.3)(1 - \gamma_1)A_1P_1^{-1.7} + (P_1(1 - Q_1) - 5.1)\gamma_1A_1P_1^{-1.7} \]

\[ R_{NP}^o = 39.2 \times 10^6 \]

\[ R_{NC} = P_1Q_1\gamma_1A_1P_1^{-1.7} = Q_1\gamma_1A_1P_1^{-0.7} \]

\[ R_{NC}^o = 0 \]

\[ 0 \leq \gamma \leq 1, \quad 0 \leq Q \leq 1 - \frac{5.1}{P_1} \]

\[ \text{Max } R = (R_{NP} - R_{NP}^o)(R_{NC} - R_{NC}^o) \]

\[ P_1Q_1\gamma \]

The bargaining result is
\begin{align*}
P_1 &= \$11/Kg, \quad Q_1 = 0.54, \quad \gamma_1 = 0.28 \\
R_{NP} &= 64 \times 10^6, \quad R_{NC} = 21.9 \times 10^6
\end{align*}

The world price for cobalt is set at $11/Kg with 0.28 of the net world demand being satisfied by offshore production. The mining consortia collect a technology royalty of $5.94/Kg of oceanbed cobalt mined by the NP.

The NC, through the mining consortia which license their technology earn rents exclusively from royalties on technology, while the NP earn rents from onshore production. It is observed that the rents from offshore production are appropriated completely by the royalties on technology.

(ii) Cobalt and Nickel

The objective function of the NP and NC are expanded to include the action in the nickel market.

\begin{align*}
R_{NP} &= (P_1 - 4.3)(1 - \gamma_1)A_1P_1^{-1.7} + (P_1(1 - Q_1) - 5.1)\gamma_1A_1P_1^{-1.7} \\
&\quad + (P_2 - 1.6)(1 - \gamma_2)A_2P_2^{-1.7} + (P_2(1 - Q_2) - 1.9)\gamma_2A_2P_2^{-1.7} \\
R_{NP}^* &= 814.2 \times 10^6 \\
R_{NC} &= Q_1\gamma_1A_1P_1^{-0.7} + Q_2\gamma_2A_2P_2^{-0.7} \\
R_{NC}^* &= 0 \\
0 &\leq \gamma_1 \leq 1, \quad \gamma_2 = \frac{7A_1P_1^{-1.7}}{A_2P_2^{-1.7}} \gamma_1 \\
0 &\leq Q_1 \leq 1 - \frac{5.1}{P_1}, \quad 0 \leq Q_2 \leq 1 - \frac{1.9}{P_2}
\end{align*}
$\text{Max } R = (R_{\text{NP}} - R_{\text{NP}}^0) (R_{\text{NC}} - R_{\text{NC}}^0)$

The bargaining solution is

$P_1 = \$8.28/\text{Kg}, P_2 = \$4.25/\text{Kg}, Q_1 = 0.38, Q_2 = 0.55, \gamma_1 = 1, \gamma_2 = 0.23.$

$R_{\text{NP}} = \$1340 \times 10^6, R_{\text{NC}} = \$422 \times 10^6.$

The world price for cobalt is set at $8.28/\text{Kg}$ and the output share of ocean mining is decided at 1. The royalty on technology is fixed at $3.15/\text{Kg}$ of cobalt.

The world of nickel is set at $4.25/\text{Kg}$ and the output share of ocean mining is fixed at 0.23 of the net world demand. The royalty on technology is fixed at $2.34/\text{Kg}$ of mined nickel.

In this case the Enterprise can either produce the cobalt and nickel from the deep oceanbed, paying the mining firms a total technological royalty of $422 \times 10^6$ or the mining consortia can produce directly, turn over the cobalt and nickel to the Enterprise charging a fee for its technology (which includes management). In either event, the rents of production from offshore mines are almost entirely appropriated by the royalty on technology so that the bulk of the rents for the NP, $1340 \times 10^6$, derive from the onshore production of nickel. The NP for cobalt phase out all land-based production and they are implicitly compensated for loss of rent through the price of nickel as described under Scenario 1.

(iii) Cobalt, Nickel and Copper

The objective function of the NP and NC is the combination of the objective functions of actors in the cobalt, nickel and copper markets.
\[
R_{NP} = (P_1-4.3)(1-\gamma_1)A_1P_1^{-1.7} + (P_1(1-Q_1)-5.1)\gamma_1A_1P_1^{-1.7}
\]
\[
+ (P_2-1.6)(1-\gamma_2)A_2P_2^{-1.7} + (P_2(1-Q_2)-1.9)\gamma_2A_2P_2^{-1.7}
\]
\[
+ (P_3-1.1)(1-\gamma_3)A_3P_3^{-1.48} + (P_3(1-Q_3)-1.5)\gamma_3A_3P_3^{-1.48}
\]
\[
R_{NP}^0 = 1744.3 \times 10^6
\]
\[
R_{NC} = Q_1\gamma_1A_1P_1^{-0.4} + Q_2\gamma_2A_2P_2^{-0.7} + Q_3\gamma_3A_3P_3^{-0.48}
\]
\[
R_{NC}^0 = 0
\]
\[
0 \leq \gamma_1 \leq 1, \quad \gamma_2 = \frac{7A_1P_1^{-1.7}}{A_2P_2^{-1.7}}, \quad \gamma_3 = \frac{6A_1P_1^{-1.7}}{A_3P_3^{-1.48}}
\]
\[
0 \leq Q_1 \leq 1 - \frac{5.1}{P_1}; \quad 0 \leq Q_2 \leq 1 - \frac{1.9}{P_2}; \quad 0 \leq Q_3 \leq 1 - \frac{1.5}{P_3}
\]
\[
\text{Max } R = \left( R_{NP} - R_{NP}^0 \right) \left( R_{NC} - R_{NC}^0 \right)
\]
\[
P_1, P_2, P_3, Q_1, Q_2, Q_3, \gamma_1
\]

The bargaining solution is

\[
P_1 = 5.40/\text{Kg}, \quad P_2 = 4.85/\text{Kg}, \quad P_3 = 3.75/\text{Kg}
\]
\[
Q_1 = 0.06, \quad Q_2 = 0.61, \quad Q_3 = 0.60
\]
\[
\gamma_1 = 1.00, \quad \gamma_2 = 0.59, \quad \gamma_3 = 0.19
\]
\[
R_{NP} = 3630 \times 10^6, \quad R_{NC} = 1530 \times 10^6.
\]

The world price of cobalt is set at $5.40/Kg and the entire net demand market is satisfied by production from offshore mines. The royalty on technology is fixed at $0.32/Kg. The world price for nickel is set at $4.85/Kg.
and 0.59 of the world net demand is satisfied by offshore production. The royalty on technology is decided at $2.96/Kg. The world price for copper is set at $3.75/Kg and 0.19 of the world net demand is satisfied from offshore production. The royalty on technology for copper is fixed at $2.25/Kg.

The NC through the mining consortia derive their rents from royalty on technology which appropriates most of the rents from offshore production. While the NP keep control over the sales of the three minerals, they essentially derive rents only from the onshore production of nickel and copper, since the onshore production of cobalt is phased out. The NP for cobalt are assumed, as before, to be compensated for the loss of rent through the prices of copper and nickel.

The solution implies that about 8 mines will be operated to satisfy the net demand if the Enterprise produces by itself. If the Enterprise purchases the technology from the consortia it will produce copper and nickel for itself, but cobalt for the NC, who will have to reimburse the Enterprise for the costs of production. Conversely, the mining consortia could produce operating 2 mines each (consequently 10 mines in all would be needed), keeping the cobalt and turning over the copper and nickel to the Enterprise after being compensated for production costs and a technology fee.
SCENARIO 3: BOTH THE NP AND NC PRODUCE; TRANSFER PAYMENTS

In this scenario, the institutional aspects modeled in Scenarios 1 and 2 are combined and extended. The NP produce from offshore mines through the Enterprise and the NC produce as well through ocean mining consortia. The NP or the Enterprise buy the technology needed for deep seabed mining from the mining consortia who in turn pay a production royalty on oceanbed production.

The model is consistent with many of the institutional arrangements that have been proposed at UNCLOS III. The mining consortia are permitted to derive rents from production and technology while the Enterprise derives rents from production as well as from being a renter that extracts a royalty on every unit of deep seabed minerals harvested by the consortia.

The policy variables are the world price, \( P \), the output share of oceanbed production, \( \gamma \), the offshore production of the NP, \( \theta \), the royalty on technology \( Q \) and the royalty on production \( Z \). The upper bound on the royalties is the point at which the rents of the user are driven to zero. This establishes the limit value of technology and production royalty.

The process constraints on oceanbed production are introduced explicitly. Cobalt is first modeled by itself and then, as earlier, nickel and copper are added. The purpose of this scenario is to model aspects of the UNCLOS III, to investigate the distribution of rents under such an institutional arrangement, to investigate the outcome of various policy variables and to track the consequences of linking cobalt, nickel and copper in a joint commodity agreement where transfer payments to actors in the 3 mineral markets are implicitly incorporated in the solutions to the policy variables, especially the prices and market shares.
Cobalt

The rents to the NP are the rents from onshore and oceanbed production plus the royalty on NC production less the royalty on technology. The rents to the NC are the rents of production plus the rents on technology sold to the NP less the royalty on production.

\[ R_{NP} = (P_1-4.3)(1-\gamma_1)A_1P_1^{-1.7} + (P_1(1-Q_1)-5.1)\gamma_1\theta_1 A_1P_1^{-1.7} + \gamma_1Z_1(1-\theta_1)A_1P_1^{-0.7} \]

\[ R_{NC} = (P_1(1-Z_1)-5.1)(1-\theta_1)\gamma_1 A_1P_1^{-1.7} + Q_1\theta_1 A_1P_1^{-0.7} \]

\[ R^o_{NP} = 39.2 \times 10^6 \]

\[ R^o_{NC} = 0 \]

\[ 0 \leq \theta_1, \gamma_1 < 1; \quad 0 \leq Z_1, Q_1 \leq 1 - \frac{5.1}{P_1} \]

\[ \text{Max } R = (R_{NP} - R^o_{NP}) R_{NC} - R^o_{NC} \]

The bargaining outcome is

\[ P_1 = 11.7/\text{Kg}, \quad Q_1 = 0.564, \quad Z_1 = 0.56, \quad \theta_1 = 0.54, \quad \gamma_1 = 0.48. \]

\[ R_{NP} = 81.99 \times 10^6, \quad R_{NC} = 20.57 \times 10^6. \]

The world price is set at $11.7/\text{Kg}, the royalty on technology at 56.4% of the price and the royalty on production at 56% of the price. The output share of ocean minerals is 48% of the net demand market and of this output share, 54% is allocated to the Enterprise or the NP. The net demand market share of the NC or the mining consortia is 0.22.

Of the total rents of about $82 \times 10^6 accruing to the NP, $17.2 \times 10^6 are from the royalties on oceanbed production. Of the rents accruing to the
NC, $20.4 \times 10^6$ are from the technology royalty. This implies that most of the rents to NC are in the form of technological rents because after paying a production royalty to the NP, the effective price the NC are able to realize is $5.15$/Kg which is almost their marginal cost of production. The effective price for oceanbed production the NP are able to realize in turn after paying the rent on technology is $5.10$ which is equal to the marginal cost of production.

(ii) Cobalt and Nickel

\[
R_{NP} = (P_1-4.3)(1-\gamma_1)A_1P_1^{-1.7} + (P_1(1-Q_1)-5.1)\gamma_1 \theta_1 A_1 P_1^{-1.7} \\
+ \gamma_1 Z_1(1-\theta_1)A_1P_1^{-1.7} + (P_2-1.6)(1-\gamma_2)A_2P_2^{-1.7} + (P_2(1-Q_2)-1.9) \\
\gamma_2 \theta_2 A_2P_2^{-1.7} + \gamma_2Z_2(1-\theta_2)A_2P_2^{-0.7}
\]

\[
R^o_{NP} = 814 \times 10^6
\]

\[
R_{NC} = (P_1(1-Z_1)-5.1)(1-\theta_1)\gamma_1 A_1 P_1^{-1.7} + Q_1 \theta_1 \gamma_1 A_1 P_1^{-0.7} + (P_2(1-Z_2)-1.9) \\
(1-\theta_2)\gamma_2 A_2 P_2^{-1.7} + Q_2 \theta_2 \gamma_2 A_2 P_2^{-0.7}
\]

\[
R^o_{NC} = 0
\]

\[
0 \leq \theta_1 \theta_2 \gamma_1 \leq 1; \quad 0 \leq Z_1, Q_1 \leq 1 - \frac{5.1}{P_1} \\
0 \leq Z_2, Q_2 \leq 1 - \frac{1.9}{P_2}; \quad \gamma_2 = \frac{7A_1 P_1^{-1.7}}{A_2 P_2^{-1.7}} \gamma_1
\]

\[
\text{Max } R = \frac{(R_{NP} - R^o_{NP})(R_{NC} - R^o_{NC})}{P_1 P_2 \gamma_1 Q_1 Q_2 Z_1 Z_2 \theta_1 \theta_2}.
\]
The bargaining solution is

\[ P_1 = 8.27/\text{Kg}, P_2 = 4.25/\text{Kg}, Q_1 = 0.38, Q_2 = 0.55 \]

\[ \gamma_1 = 1, \gamma_2 = 0.23, Z_1 = 0, Z_2 = 0, \theta_1 = 0, \theta_2 = 0. \]

\[ R_{NP} = 1340 \times 10^6, R_{NC} = 423 \times 10^6. \]

The world price for cobalt is set at $8.27/Kg and the output share of deep ocean mining is equal to the entire net demand market, all of which is allocated to the mining consortia. No production royalty is paid for extracting cobalt and since the Enterprise does not produce any cobalt from offshore mines no technology royalty is paid although it is set at $3.14/Kg.

The world price for nickel is set at $4.25 and the output share of ocean mining is fixed at 0.23 of the net world demand. All offshore production is allocated to the mining consortia. The NP for nickel retain 0.77 of the net demand market. There is no royalty on production and since the Enterprise engages in no mining, no royalty on technology is paid even though it is set at $2.34/Kg.

The NC, through the consortia, earn rents of $423 \times 10^6 while the NP for nickel earn rents of $1340 \times 10^6. The NP for cobalt earn no rents. The implicit transfer payments discussed under Scenario 1 are presented too [?]. It may be recalled that many of the NP for cobalt are also NP for nickel, so that transfer payments can take place through the price of nickel, which is presumably set at a level that compensates for the loss of rents from onshore cobalt production. Moreover, the only NP for cobalt that has neither a nickel nor a copper operation will cease to be a producer of any significance by 1985, so that its case for explicit transfer payments may be a very tenuous one.

In contrast with the analysis for cobalt alone it is noticed that while
the NP has 0.78 of the market, here they have none. While transfer payments on both technology and production took place in that case, none are made here, and while the price of cobalt was set at $11.7/Kg in the earlier case, it is set at $8.27/Kg, which is lower than 1976 real prices, here. The consumers for cobalt gain as do the mining consortia. Onshore production of cobalt is phased out.

Finally, it is seen that the total rents to the NP and NC are almost identical under both scenarios 1 and 2, as is the allocation of output shares to ocean mining and the world prices for cobalt and nickel. The difference, of course, is that in Scenario 1 the mining consortia produce on behalf of the Enterprise which pays them a rent on technology while in Scenario 2 the mining firms produce for themselves and do not, obviously, collect rents on technology from the Enterprise whose role clearly is much reduced. At best it becomes a focus for negotiating between the NP and the NC.

(iii) Cobalt, Nickel and Copper

\[
R_{NP} = (P_1 - 4.3)(1 - \gamma_1)A_1P_1^{-1.7} + (P_1(1 - Q_1) - 5.1)\gamma_1 \theta_1 A_1 P_1^{-1.7}
\]

\[
+ \gamma_1 Z_1(1 - \theta_1)A_1 P_1^{-0.7} + (P_2 - 1.6)(1 - \gamma_2)A_2 P_2^{-1.7}
\]

\[
+ (P_2(1 - Q_2) - 1.9)\gamma_2 \theta_2 A_2 P_2^{-1.7} + \gamma_2 Z_2(1 - \theta_2)A_2 P_2^{-0.7}
\]

\[
+ (P_3 - 1.1)(1 - \gamma_3)A_3 P_3^{-1.48} + (P_3(1 - Q_3) - 1.5)\gamma_3 \theta_3 A_3 P_3^{-1.48}
\]

\[
+ \gamma_3 Z_3(1 - \theta_3)A_3 P_3^{-0.48}
\]

\[
R_{NP}^O = $1744.3 \times 10^6
\]
The bargaining solution is

\[ P_1 = \$5.41/Kg, P_2 = \$4.85/Kg, P_3 = \$3.76/Kg \]

\[ Q_1 = 0.06 \quad Q_2 = 0.61 \quad Q_3 = 0.60 \]

\[ \gamma_1 = 1 \quad \gamma_2 = 0 \quad \gamma_3 = 0.19 \]

\[ Z_1 = 0 \quad Z_2 = 0 \quad Z_3 = 0 \]

\[ \theta_1 = 0 \quad \theta_2 = 1 \quad \theta_3 = 0 \]

\[ R_{NP} = 3630 \times 10^6 \quad R_{NC} = 1530 \times 10^6 \]

The world price for cobalt is set at \$5.41/Kg and all the net demand is satisfied by offshore production. The mining consortia are allocated
the entire share of oceanbed production. No production royalty is paid and, if applicable, the royalty on technology would be $0.32/Kg of cobalt mined.

The world price for nickel is set at $4.85/Kg and 0.59 of the net world demand is satisfied by offshore production. The entire offshore production is allocated to the NP or the Enterprise acting on their behalf. There is no royalty on production but the royalty on technology is $2.96/Kg of nickel mined from the deep seabed. The world price of copper is set at $3.76/Kg and 0.19 of the world net demand is satisfied by offshore production, all of which is allocated to the mining consortia. Again, there is no royalty on offshore production and the royalty on technology, if applicable, would be $2.26/Kg.

The rents to the NC are $1530 x 10^6 and to the NP are $3630 x 10^6. It may be noted that all rents the NP realize from offshore production are essentially captured by the royalties on technology. In effect, the NP realize rents from onshore production of nickel and copper only. To the extent that they are able to maintain a substantial market share in the copper market and the entire share of the net nickel market, they may be able to keep control over the markets and derive utility from this.

The NC earn rents from production as well as royalties on technology. The royalty is from technology in account for about $917 x 10^6 out of a total rent of $1530 x 10^6.

Once again, the NP for cobalt lose their rents entirely, but again, it is supposed they are compensated for this loss by the implicit transfer payments reflected in the prices and market shares for copper and nickel.

Operationally, the results of the game model for this case can be
interpreted in two ways. Since it would not be practical for the consortia to mine only cobalt and copper and for the Enterprise to mine only nickel, either one or the other will have to mine all three minerals (this is optimal in terms of marginal costs since the ferromanganese deposits are a joint product resource) and then make physical transfers in exchange for rents or royalties.

In one arrangement the mining consortia could produce the cobalt, nickel and copper and then transfer the nickel to the Enterprise, charging it a royalty on technology and mining expenses. In the other arrangement, the Enterprise could buy the mining technology from the consortia, produce from the deep seabed, keep the nickel and transfer the copper and cobalt to the NC. This, however, is not as practical as the first arrangement, since the consortia could quite easily produce on their own because they already possess the technology.

The addition of copper to the model changes the earlier outcomes for cobalt and nickel. The price of the former is driven from $8.27/Kg (see Scenario 1.3 (ii)) to $5.41/Kg. The price of the latter, on the contrary is driven up from $4.25/Kg to $4.86/Kg and its output share of offshore production goes from 0.23 to 0.59 of the net worth demand market. Moreover, the entire oceanbed production is allocated to the NP in this case, whereas earlier it went to the NC.

(iv) Cobalt, Nickel and Copper with Constrained Copper Prices

The earlier formulation is slightly modified here by constraining the upper limit of the price of copper to $2.50/Kg. This is an attempt to investigate how the bargained solution would change if there were an international commodity agreement on copper that kept its price between established limits. While the figure of $2.50/Kg was chosen somewhat
arbitrarily, it does reflect the historical high reached by copper prices in the past decade. To that extent, it may provide the basis for an agreed upper price limit incorporated in a producer-consumer association modeled after the International Tin Agreement. Copper has been designated an UNCTAD "core" commodity and some agreement on stabilizing may not be far in the future.

The bargaining outcome of this case is shown in Table 4.2 and compared with the unconstrained case. While the price of copper attains the upper limit of $2.50/Kg, the price of cobalt declines to $5.3/Kg from $5.41/Kg, the price of nickel rises sharply to $5.44/Kg from $4.85/Kg. Total rents to the NP fall slightly to $3550 x 10^6 from $3630 x 10^6, while those accruing to the NC fall somewhat as well, from $1530 x 10^6 to $1420 x 10^6. In percentages, however, these declines are small. The fall in the price of copper is clearly compensated for by the rise in the price of nickel. As a group, the NP and NC try to protect total rents by negotiating on the prices of all three minerals simultaneously, so that in a joint commodity agreement if price limits are imposed on one commodity, the prices of others are influenced as well. Indeed, the impact of a price limit extends to other variables as well. The output shares of ocean minerals rises to 0.74 from 0.59 for nickel but falls from 0.19 to 0.11 for copper. It is unchanged for cobalt.

The biggest change, however, is in market shares. The share of deep seabed output for copper is allocated entirely to the NP or the Enterprise which is the complete opposite of the unconstrained case. Moreover, the net demand share of the NP for nickel goes to 1.0 from 0 and for copper it goes to 1.0 from 0.81. As a consequence, the composition of rents to the NC or the mining consortia changes. They now
### TABLE 4.2
Comparison of 2 Versions of Scenario 3

<table>
<thead>
<tr>
<th>Model Outcome</th>
<th>Copper Prices Unconstrained</th>
<th>Copper Prices Constrained to an Upper Limit of $2.50/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{NP}$</td>
<td>$3630 \times 10^6$</td>
<td>$3550 \times 10^6$</td>
</tr>
<tr>
<td>$R_{NC}$</td>
<td>$1530 \times 10^6$</td>
<td>$1420 \times 10^6$</td>
</tr>
<tr>
<td>$P_1$</td>
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<td>$5.44$/Kg</td>
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<td>Market-Shares of NP for</td>
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</tr>
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<td>0.00</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Copper</td>
<td>0.81</td>
<td>1.00</td>
</tr>
</tbody>
</table>
derive the bulk of their rent from royalties on technology used to produce nickel and copper from the deep seabed.

Operationally, too, the results could be interpreted as having changed from the unconstrained case. Since the entire production share for copper and nickel from offshore mines now goes to the NP, the Enterprise could engage in mining after buying the technology from the mining consortia. The Enterprise would discover, however, that while it has complete control over the sales of nickel and copper, its rents from offshore production are almost completely appropriated by the royalties paid for the technology.
CONCLUSIONS

The results of this chapter are summarized in Tables 4.3 and 4.4. Table 4.3 presents a comparison of the preferred model across scenarios moving from cobalt to cobalt and nickel, and finally to cobalt, nickel and copper. Table 4.4 presents a comparison of offshore production and NP market shares for the 3 scenarios with cobalt, nickel and copper considered together. The implications of these results and the analysis contained in this chapter are enumerated below.

1. Negotiated Outcomes

A negotiated outcome over the division of rents, the establishment of prices and allocation of market shares dominates a non-negotiated outcome except in those cases where consumer surplus is explicitly considered. Even here a negotiated outcome may be preferable because there could be sound political reasons for sacrificing some consumer surplus. Indeed, it is the revealed preference of official negotiators from the U.S., Western Europe and Japan to trade consumer surplus versus non-economic gains such as stability in commodity markets,* enhanced national security through reduced global tension and access to secure sources of supply. Further, the practical policy decisions pertaining to the New Economic Order and a desire to secure greater international egalitarianism require that some consumer surplus be translated to the NP from the South through higher prices for some minerals. Producer units from the NC also benefit by this agreement. Here again, it may be noted that the revealed preference of U.S. negotiators at the UNCLOS

*The Economist of London has kept an especially keen eye on developments. See for instance the report "Commodities Fund," March 25, 1978, pp.91-92. (Footnote continued on next page.)
## Comparison of the Three Scenarios (Preferred Model)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>No. of Deep Sealed Mines Operated</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Cobalt, Copper, Nickel</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Cobalt, Copper, Nickel</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Cobalt, Copper, Nickel</td>
</tr>
</tbody>
</table>

### Table 4.3

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario</td>
<td>Offshore Production Share</td>
<td>Copper</td>
<td>Nickel</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
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<td>1.00</td>
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</tr>
<tr>
<td>3</td>
<td>0.81</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Offshore Production Shares and Market Shares of the NP in the Preferred Model

**TABLE 4.4**
III is in favor of securing terms acceptable to international mining consortia based largely in the U.S. and dominated by U.S. firms. In the arena of domestic policy as well, the bias is clearly in favor of the producers since the various bills** before Congress that relate to oceanbed mining all draw their inspiration from a measure originally drafted by the U.S. Mining Congress.

*(footnote continued from previous page) The U.S. primarily views commodity agreements as a way of responding to the constraints of interdependence (as the cost, merely, of consumer surplus in that particular market) and as a forum for bargaining between the NP and NC. The U.S. Secretary of the Interior has observed that "Current U.S. interest in international commodity policy is partly the result of increasing pressure from developing countries for special international agreements to regulate commodity prices" and noted that "Producer organizations in many industries are becoming councils where producers and consumers can carry out specific negotiations," Mining and Minerals Policy 1977, Annual Report of the Secretary of the Interior (Washington, D.C.: January 1977), p. 146.

In Western Europe the tendency of the EEC to sacrifice consumer surplus through the formation of European cartels is too well known to require elaboration here. The most recent attempts at helping producers of steel, synthetic fibers and petrochemicals is through the formation of an EEC Industry Commissioner. For a disapproving comment on this refer to "Davignon's dangerous path," The Economist, April 22, 1978, pp. 88-89. For yet another example of producer rents being protected at the expense of consumer surplus, note the recent talks among officials from the U.S., Japan and the EEC on formulating a world steel agreement. A report of the meeting is provided in "Towards a World Steel Cartel," The Economist, April 29, 1978, p. 95.

2. Linking Markets

The impact of linking the international commodity markets for cobalt, nickel and copper in a joint bargaining game is a convergence in their prices. The price of cobalt falls as its market is linked first with nickel and then with nickel and copper. The price of nickel rises as its market is linked with the other two minerals and the price of copper rises significantly because of the linkage.

The NP and NC are interested in maximizing total rents rather than rents in any particular market. The cobalt market being small in terms of rents can be bargained away to the NC in return for higher rents in the more significant nickel market and the considerably more important copper market. Consequently, the NC attain control over cobalt production, which shifts to the oceanbed as the mines of the NP are either phased out or as cobalt is no longer extracted as a by-product of copper or nickel. Once cobalt is produced from offshore mines, with their much larger reserve base (as compared to onshore mines), the price promptly falls to near marginal cost since both the NP and the NC find it more profitable to concentrate on the prices of copper and nickel.

In the case of nickel, prices rise somewhat above the relatively low 1975 levels reflecting the exertion of market power. This is quite feasible since the NP and NC must function like a two-part cartel if they are to reach a negotiated solution that is pareto-optimal. However, prices of nickel cannot really rise much above their (real) historical levels because, until recently, nickel prices were close to the monopoly point for INCO, long the world's dominant and lowest cost producer.
The price of copper rises most significantly above 1975 levels because it is the market that provides the greatest opportunity for increases in rent. The 1975 price for copper was unusually depressed and the market is certainly the most competitive of the three. Cartelization, therefore, affords the incentive and the opportunity for exercising unutilized market power and this is reflected in the almost doubling of the price of copper, from levels close to the marginal costs of production.

3. Level of Rents

The level of total rents remains quite stable across scenarios even though the composition changes. This suggests that the different institutional approaches modeled in the scenarios are essentially distribational in their impact. The model outcomes are different aspects of the same economic game, which ultimately is a function of marginal costs, prices and net demand shares. The different institutional arrangements do not, therefore, change the total rents available for distribution, but rather the components of these rents. This, incidentally, serves to validate the internal consistency of the game model.

4. Rents to Technology

Much of the rent from offshore production is appropriated by the proprietary technology of the mining consortia. It is not surprising that in the case of deep oceanbed mining all surplus, i.e. the difference between market price and marginal costs, should be appropriated by the owners of technology rather than land, since significant advances in technology are necessary for successful offshore mining. Land-based mining technology, on the other hand, is well tested and widely dispersed so that it can hardly command much rent. In theory, therefore, it becomes
immaterial whether the mining consortia produce themselves or license their technology to the Enterprise which produces on its own, because the rental component of price in either case is the royalty on technology.

5. Pricing Strategies

The solutions to the game model suggest pricing strategies for the NP for cobalt, nickel and copper. The NP for cobalt, perceiving their total loss of market share by 1985-1990, might follow a strategy of short-term rent maximization by gradually raising the price of cobalt in 1975 dollars until they reach the point of short-run profit maximization. New land-based producers will have little incentive to make the capital investments necessary to enter the industry, since production will be switched to the oceans anyway, and consumers will not find it worthwhile to invest in technological change and substitutes if cobalt prices are expected to fall to levels close to the marginal cost of offshore production by 1985-1990. The NP for nickel might wish to maintain fairly stable prices to discourage any further entry since they will realize higher prices and greater rents by 1985-1990 as a consequence of a negotiated solution with the NC. To do this, however, they will need to maintain their bargaining position by keeping the industry concentrated. The argument for relatively low, stable prices for the NP for copper is even stronger, because of the anticipated high prices and rents after a negotiated solution. A reasonably low price trajectory until 1985-1990 will be both an effective barrier to entry and result in a greater share of the market of higher cost producers such as the U.S. Both these factors will lead to a strengthening of the bargaining power of the NP and lead to the anticipated high price negotiated outcome.
6. Economic Bargaining Power

The economic bargaining power of the NP is a function of their lower marginal costs. However, as the technology to develop S-Resources improves, the scale of operations increases and the corporations from the NC gain experience in working in the environment of the deep ocean, the Antarctic, and space, the difference between the marginal costs of the NP and the NC will decline. Further, within 20 years or so as land-based reserves are gradually depleted, the cost of production will increase hyperbolically, which in turn will erode the difference between marginal costs. In any event, as far as the S-Resources are concerned, the bargaining power of the NC, as expressed in the game model, will increase. It is in the long term interests of the NP, therefore, to secure an international treaty governing the distribution of rent from S-Resources by coming to some agreement, at the least, on world prices and market-shares.

It might be argued that a competitive solution, as opposed to a de facto two-part cartel is the best promoter of global welfare and resource allocation. This, however, would not be politically feasible. The dissipation of oligopoly or monopoly rent would hardly be tolerated by the nations of the South, who view increasing their economic rent from resource development as part of a general strategy of global redistribution of income. Given the current international political penchant for orderly marketing agreements, producer groups and producer and consumer agreements (as typified by the UNCTAD core commodity negotiations) a two-part cartel recommends itself as an action based on political economy, if not on the pure economics of smoothly adjusting competitive markets.

Much of the technology required to develop S-Resources is the pre-
serve of corporations based in the U.S., Japan and W. Germany. If there is no agreement or if the NP pursue a policy of economic confrontation, then the development of S-Resources will certainly be delayed, but equally, it will not be forever prevented, since the NC will have a long term incentive to ignore the emerging concept of the 'common heritage of mankind' and pursue a unilateral and self-serving economic policy towards the deep oceanbed, the Antarctic and space. Whether the NC and especially the U.S., Japan and W. Germany have the political will to forge a new imperial order needed to do this is a subject rife with speculation and predictions are fraught with uncertainty. The constraints of interdependence and international egalitarianism determine the relative political bargaining power of the NP and the NC. In the near future the NP may have a growing bargaining advantage, but in another 20 years, the perceptions of the NC may change as the rents to be derived from the unilateral exploitation (failing an international treaty) of S-Resources become increasingly attractive. If resources scarcities and the persistent threat of economic confrontation begin to irk the citizens of the advanced industrialized nations, then the desire to secure international egalitarianism may decrease and if that happens, the NP may find their political bargaining power eroding rapidly.

Finally, there is the matter of structural changes within the NP and its consequences for the bargaining power of that group. In the case of cobalt, Zaire is, at present, the undisputed price setter. In a few years, however, this situation may change as lateritic deposits yielding nickel and cobalt as co-products are developed in New Caledonia. The NP will have to expand their membership. If the mar-
ginal costs of producing in New Caledonia are comparable to those of ocean mining, Zaire may be able to discipline the new member with threats of price cutting. If, however, the marginal costs are closer to those of Zaire, then the latter's price setting position may be jeopardized.

In the case of copper, the position is somewhat different. There may be a tendency for the bargaining power of the NP to increase in the short run, if Chile, which is probably the lowest marginal cost producer, can expand output rapidly enough to increase its market share. U.S. producers have expressed some alarm at Chile's plans after noting that Chilean production in 1977 was 6% more than in 1976, and in 1976 it increased production by 21% over the 1975 levels. The marginal cost of production in the U.S. is over $1/Kg for new mines, whereas in Chile it could be about 60¢/Kg or less. The cost of transportation from Chile to the U.S. or Western Europe is about 6¢/Kg, so that Chilean copper has a considerable competitive advantage. Indeed, in January 1978, Chile was making one year contracts with U.S. customers at the London Metals Exchange price of $1.25/Kg, as opposed to the U.S. producers' price of $1.39/Kg (Metz, 1978).

The world nickel market, too, is changing. For many years, it, like the cobalt market, had been characterized by a monopolistic producer and a price taking fringe. The monopolist, INCO Ltd. (of Canada) had virtually developed the industry and the markets and its price setting role was undisputed. That role, however, has been seriously challenged in recent years and in 1977 INCO suspended its policy of posting prices, thus providing an umbrella for other producers, and declared it would enter into price competition by letting prices fluctuate according to market conditions. This was merely a reflection of decaying market power. In
1950, the firm had accounted for 90% of the non-communist market. By 1970 its share was reduced to 50% of a considerably bigger market. INCO's comparative advantage of control over high grade ores in Ontario, Canada was gradually negated by technological developments that made possible the profitable production of nickel from lateritic ores common in the nations of the South. Supply pressure at present comes from such nations as New Caledonia, Indonesia and Guatemala. Indeed, over-capacity and rapidly increasing supplies in the world nickel market have forced INCO, Societe Metallurgique Le Nickel (owned jointly by Societe Imetal and Societe National Elf Aquitaine) and Falconbridge Nickel Mines Ltd. of Canada, among other producers, to institute cut-backs in production in an effort to restore nickel prices. In such an environment, the bargaining power of the NP versus the NC is certain to decay.

While the NC will try to further reduce their dependence on the NP by extracting nickel from the seabed, the NP may be expected to try to acquire some control over that potentially troublesome new source of supply. INCO, in an attempt to control both land-based and offshore supplies, has formed a mining consortium to develop ferromanganese nodules. In this regard it is merely acting like a well-behaved monopolist. Its strategy seems to be to try and position itself in the camps of both the NP as an onshore producer, and the NC as one of a group of firms that will operate out of the U.S. and engage in offshore mining, so that whatever rents it loses from onshore production it could make up by rents from technology or both, from offshore production.

Trends in the non-communist producer concentration of the three minerals are shown in Table 5. The Herfindahl-Hirschman index of concentration has been computed for 1965, 1970 and 1975. The decline of
INCO is evident from the falling index for nickel. The index for cobalt shows mainly the relative changes in Zaire's pre-eminence and continues to be high. The falling index for copper is testimony to increasing global competition and the relative decline of the U.S. and Canada as members of CIPEC increase output.

**TABLE 4.5**

Herfindahl-Hirschman Index of Non-Communist Producer Concentration

<table>
<thead>
<tr>
<th>YEAR</th>
<th>COBALT</th>
<th>NICKEL</th>
<th>COPPER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>0.349</td>
<td>0.590</td>
<td>0.172</td>
</tr>
<tr>
<td>1970</td>
<td>0.492</td>
<td>0.385</td>
<td>0.167</td>
</tr>
<tr>
<td>1975</td>
<td>0.394</td>
<td>0.231</td>
<td>0.131</td>
</tr>
</tbody>
</table>

Notes:
(a) The H-H index is the sum of the squares of the market shares.
(b) The communist countries are generally a closed system with respect to these minerals.
APPENDIX 1: DEEP OCEAN MINE SITES

It has been suggested for engineering and economic reasons that a mine site be defined as an area capable of yielding 3 million dry metric tons of nodules per year for 20 years (Pasho and McIntosh, 1976), i.e. an area of the deep ocean bed that has recoverable reserves of 60 million dry metric tons of nodule. Moreover, the nodules must have a minimum average grade quality of 2.27% nickel and copper (Kildow et al., 1976). Finally, the sea floor topography, ocean currents and weather conditions must be such that mining is physically possible. These three conditions, abundance, grade quality and physical environment, define a mine site.

An area of the ocean bed where the minimum grade quality is satisfied is termed 'prime.' An analysis using the SIO Sediment Data Bank at the Scripps Institution of Oceanography reveals that most of the prime area is in the northeast equatorial Pacific region (Frazer, 1977), and covers 1.37 million square kilometers. The nodule abundance in areas with a sufficient concentration to mine (greater than 5 Kg/m² -- Kaufman, 1974) is 11 Kg/m².

Even after a mine site has been selected to obtain the optimal sea floor topography, it is estimated that 20% of the mine site will be inaccessible owing to the presence of obstructions (Kaufman, 1974). The mining dredge head will have an estimated efficiency of 60% and the mining sweep efficiency will be about 65% (Kaufman, 1974). This leads to a recovery efficiency of 20%.

Since a mine site must yield 60 million tons of dry nodules and wet nodules contain about 30% water, this requires 86 million wet tonnes of recoverable nodules per site. Since the recovery efficiency is 20%, a mine site must have a required abundance of 430 million tonnes. A square meter of the mine site contains 11 Kg of nodules so that the area of a mine site must be 3.9 x 10⁴ square kilometers.
The total prime area has been estimated at \(1.37 \times 10^6\) square kilometers, which suggests that there are probably 35 first generation mine sites.* With more sophisticated technology or a higher price for the ore, the number of mine sites could increase substantially. There is, however, no estimate of the price elasticity of recoverable reserves.

The value of 1 tonne of mineable manganese nodules (when only cobalt, nickel and copper are extracted) from a representative mine site is about $101, on the basis of 1976 prices, as shown in Table 1. Ocean mining recoverable reserves and land-based reserves are presented in Table 2. World production of manganese, nickel, cobalt and copper for 1975 and 1976 is shown in Table 3.

### TABLE 1

**Value of 3 Minerals in 1 Metric Ton of a Representative Sample of Manganese Nodules**

<table>
<thead>
<tr>
<th>Metal</th>
<th>% of 1 Dry Ton</th>
<th>1976 World Price $/MT</th>
<th>Value/MT $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>1.3</td>
<td>(5.06 \times 10^3)</td>
<td>65.78</td>
</tr>
<tr>
<td>Cu</td>
<td>1.1</td>
<td>(1.606 \times 10^3)</td>
<td>15.66</td>
</tr>
<tr>
<td>Co</td>
<td>0.2</td>
<td>(9.79 \times 10^3)</td>
<td>19.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$101.02</td>
</tr>
</tbody>
</table>

1 Source: Hans M. Amann, "Definition of an Ocean Mining Site," paper no. OTC 2238, Figure 7, Offshore Technology Conference, Dallas, Texas, 1975.


* This number, however, is tentative. It has been pointed out by Dr. Jane Frazer of the Scripps Institution of Oceanography that the reliability of available data concerning the grade and abundance of seabed manganese nodules is not of a nature that permits confident predictions (Frazer, 1977).
TABLE 2
Ocean Mineral Recoverable Resources Per Mine Site, Total First Generation

Ocean Mining Recoverable Reserves and Land-Based Proven Reserves (Million Metric Ton)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Reserves/Si.e</th>
<th>Total Ocean Reserves</th>
<th>Land Base Reserves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>15.36</td>
<td>537.6</td>
<td>5654.50</td>
</tr>
<tr>
<td>Ni</td>
<td>0.78</td>
<td>27.3</td>
<td>55.45</td>
</tr>
<tr>
<td>Cu</td>
<td>0.66</td>
<td>23.1</td>
<td>460.00</td>
</tr>
<tr>
<td>Co</td>
<td>0.12</td>
<td>4.2</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Source: U.S. Bureau of Mines, Commodity Data Summaries, 1977. Reserves in each case refer to ores commercially recoverable by present technology and should be viewed as the most conservative estimate of available metals. Does not include lateritic ores.

TABLE 3
World Stocks, Flow, Stock to Flow Ratio and Years to Depletion of 4 Metals (Millions of Tonnes)

<table>
<thead>
<tr>
<th>Metal</th>
<th>World Reserves*</th>
<th>Production (P) 1975 1976</th>
<th>Stock/Flow (R/P) Ratio 1976</th>
<th>Years to Depletion (YTD)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>5992.10</td>
<td>24.45 24.63</td>
<td>243.3</td>
<td>70.6</td>
</tr>
<tr>
<td>Nickel</td>
<td>82.75</td>
<td>0.818 0.800</td>
<td>103.4</td>
<td>46.8</td>
</tr>
<tr>
<td>Copper</td>
<td>483.10</td>
<td>6.98 7.39</td>
<td>65.4</td>
<td>36.8</td>
</tr>
<tr>
<td>Cobalt</td>
<td>5.85</td>
<td>0.033 0.035</td>
<td>167.14</td>
<td>59.7</td>
</tr>
</tbody>
</table>

* Not including lateritic ores.

** YTD = \[\log \left[ \frac{(R/P) \left( \frac{DP}{P} \right) + 1}{\left( \frac{DP}{P} + 1 \right) P} \right] - 1\]

\[\log \left( \frac{DP}{P} + 1 \right)\]

\[\frac{DP}{P} = 3\% \text{ (assumed annual growth rate of production)}\]
APPENDIX 2: DYNAMIC FORMULATION OF THE GAME MODEL

While the static model presented in Chapter 4 captures the essential features of the game, a dynamic model may lead to greater insights because:

(1) The NP and NC may have different discount rates, and,

(2) The threat print may vary over time owing to (a) hyperbolic marginal costs caused by resource depletion and (b) changing limit prices owing to stochastic pricing pursued by the NP as an optimal strategy to prevent mining by the NC or owing to stock adjustment effects in the supply of scrap.*

Different discount rates and hyperbolic marginal costs are modeled explicitly in a dynamic version of Scenario 1 that follows. It is not solved owing to the computational complexity of optimal control problems. Even the simple structure of Scenario 1 becomes rather unwieldy in the dynamic version. Scenarios 2 and 3 would result in computationally intractable dynamic games and hence were not modeled. A future effort may, however, attempt a solution to the problem.

\[
R_{NP} = \sum_{t=1}^{N} \frac{1}{(1+\delta_1)^t} \left[ \left( P_1 - \frac{WP_1}{FP_1} \right) B_1 A_1 (1+g_1)^{tP_1} -1.7 \\
+ \left( P_2 - \frac{WP_2}{FP_2} \right) B_2 A_2 (1+g_2)^{tP_2} -1.7 \\
+ \left( P_3 - \frac{WP_3}{FP_3} \right) B_3 A_3 (1+g_3)^{tP_3} -1.48 \right]
\]  

*Time varying limit prices are discussed in detail by David M.G. Newberry, who points out that a "monopolists optimal limit pricing strategy may involve randomizing prices even though stable prices would be feasible," in "Stochastic Limit Pricing," The Bell Journal of Economics, Vol. 9, No. 1, Spring 1978.
\[ R_{NP}^o = \sum_{t=1}^{N} \left( \frac{1}{(1+g_1)^t} \left[ \left( \frac{W_S}{F_S^1_t} - \frac{W_P}{F_P^1_t} \right) A_1 (1+g_1)^{t_p} P_{1t}^{1.7} - 1.7 \right] \right. \\
\left. + \left( \frac{W_S}{F_S^{2t}} - \frac{W_P}{F_P^{2t}} \right) A_2 (1+g_2)^{t_p} P_{2t}^{1.7} \right. \\
\left. + \left( \frac{W_S}{F_S^{3t}} - \frac{W_P}{F_P^{3t}} \right) A_3 (1+g_3)^{t_p} P_{3t}^{1.48} \right) \] (2)

\[ R_{NC}^o = 0 \] (3)

\[ B_{2t} = 1 - \frac{A_1 (1+g_1)^{t_p} P_{1t}^{1.7}}{A_2 (1+g_2)^{t_p} P_{2t}^{1.7}} \ (1-B_{1t}) \] (4)

\[ B_{3t} = 1 - \frac{A_1 (1+g_1)^{t_p} P_{1t}^{1.7}}{A_3 (1+g_3)^{t_p} P_{3t}^{1.48}} \ (1-B_{1t}) \] (5)

\[ F_{P1t} = F_{P1,t-1} - B_{1t} A_1 (1+g_1)^{t_p} P_{1t}^{1.7} \] (6)

\[ F_{S1t} = F_{S1,t-1} - (1-B_{1t}) A_1 (1+g_1)^{t_p} P_{1t}^{1.7} \] (7)

\[ F_{P2t} = F_{P2,t-1} - B_{2t} A_2 (1+g_2)^{t_p} P_{2t}^{1.7} \] (8)

\[ F_{S2t} = F_{S2,t-1} - (1-B_{2t}) A_2 (1+g_2)^{t_p} P_{2t}^{1.7} \] (9)

\[ F_{P3t} = F_{P3,t-1} - B_{3t} A_3 (1+g_3)^{t_p} P_{3t}^{1.48} \] (10)

\[ F_{S3t} = F_{S3,t-1} - (1-B_{3t}) A_3 (1+g_3)^{t_p} P_{3t}^{1.48} \] (11)

\[ \text{Max } R = (R_{NP} - R_{NP}^o) (R_{NC} - R_{NC}^o) \] (12)
where:

WP = constant related to the marginal cost of land-based production at \( t = 0 \).

WS = constant related to the marginal cost of ocean-based production at \( t = 0 \).

\( FP_t \) = land-based reserves.

\( FS_t \) = ocean-based reserves.

\( \delta_1 \) = discount rate of the NP.

\( \delta_2 \) = discount rate of the NC.

\( g \) = growth rate demand.
REFERENCES


